THE USE OF ARTHROPLASTY SURGERY IN THE TREATMENT OF SEVERE ISOLATED PATELLOFEMORAL ARTHRITIS

by

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DEDICATION

To my dearest sister Yosra, you held onto your purpose, succeeding beyond measure. When the tragedy came, you sought the blessings. You taught lessons of courage and thanks in the midst of pain and uncertainty. You inspired and encouraged me to overcome the challenges of this thesis, to silence the doubt and continue believing. Just as you taught, I will hold onto my purpose, pay it forward and neverforgettosaythankyou.

DECLARATION

I declare that this thesis is an accurate record of my results obtained by myself within the Trauma and Orthopaedic Department Clinics at University Hospitals Coventry and Warwickshire NHS Trust, Biomechanical Engineering Lab at Imperial College London and Division of Health Sciences, University of Warwick, and the data that has been generated is detailed in this thesis. All sources of support and technical assistance have been stated in the text of the acknowledgments. None of the work has been previously submitted for a higher degree.

All publications and papers presented at national and international conferences, as a result of the work described in this thesis, are listed on pages 454 and 455.

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SUMMARY

Severe isolated patellofemoral arthritis is a highly debilitating disease. Total knee arthroplasty is considered the gold standard treatment, however, patellofemoral arthroplasty has certain advantages. This 'less invasive' procedure preserves the tibiofemoral joint and cruciate ligaments, facilitating a more rapid recovery and allows for a relatively straightforward revision if required in the future. As the use of patellofemoral arthroplasty steadily gains popularity in the orthopaedic community, it is important to establish a consensus on which treatment should be the primary intervention of choice. Through background reading and expert opinion, three areas of research were chosen for further investigation:

1. Extensor mechanism efficiency
2. Survival and complication proportions following patellofemoral arthroplasty and total knee arthroplasty
3. Assessment of differences in function and quality of life outcomes following patellofemoral arthroplasty and total knee arthroplasty

The purpose of this thesis was to further inform the debate between the choice of total knee arthroplasty and patellofemoral arthroplasty for the treatment of severe isolated patellofemoral arthritis.

Study I: The cadaveric biomechanics study compared the extensor mechanism efficiency of the native knee, patellofemoral arthroplasty, cruciate-retaining total knee arthroplasty and posterior-stabilising total knee arthroplasty. Patellofemoral resultant force, peak pressure and contact area were also analysed. The data produced a bimodal distribution during the flexion-extension cycle for all four conditions. The results showed patellofemoral arthroplasty produced the greatest extensor mechanism efficiency in the range of mid flexion to extension (50° to 0°). Further research is required to determine whether this efficiency translates to the clinical setting.

Study II: The systematic review compared the survival and complication proportions of patellofemoral arthroplasty and total knee arthroplasty. The patellofemoral arthroplasty studies were divided into seven groups depending on femoral component design. Thirty-six out of the forty studies identified were uncontrolled retrospective case series' and therefore subject to reporting and selection biases and overall provided low quality evidence. A meta-analysis could not be performed due to high clinical heterogeneity. Other limitations included variations in study design and length of follow-up. Despite, these weaknesses the review established inlay designs produced the poorest survival and complication outcomes. Malpositioning/misalignment and disease progression were the most common complications.

Study III: The double-blind randomised clinical trial assessed for differences in function and quality of life outcomes between patellofemoral arthroplasty and total knee arthroplasty. The trial failed to show evidence of a difference between the two interventions. Complication rates were overall low but greater in the total knee arthroplasty group. Tests for significance were not performed due to the small numbers involved. Although, the study was underpowered, the data did not support superiority of patellofemoral arthroplasty over total knee arthroplasty. Therefore, future studies should test for non-inferiority and involve multiple centres to increase generalizability to the wider orthopaedic community.

ABBREVIATIONS

ACL	Anterior Cruciate Ligament
ADLs	Activities of Daily Living
AEs	Adverse Events
AGC	Anatomic Graduated Component (Biomet)
BMI	Body Mass Index
CLRN	Comprehensive Local Research Network
CR-TKA	Cruciate retaining Total Knee Arthroplasty
CS-TKA	Cruciate sacrificing Total Knee Arthroplasty
CTU	Clinical Trials Unit
DMC	Data Monitoring and Ethics Committee
DO	Digital Output
DVT	Deep vein thrombosis
EMG	Electromagnetic Testing
EQ5D QoL	EuroQol – quality of life health assessment
FE	Flexion:extension or flexion-extension
FPV	FemoroPatelloVialla
HSS	Hospital for Special Surgery Knee Rating Scale
IAA	inlay, asymmetrical, anatomical
IAN	inlay, asymmetrical, non-anatomical
IB I	Insall-Burstein I (Zimmer)
IB II	Insall-Burstein II (Zimmer)
ISN	inlay, symmetrical, non-anatomical
ITB	Iliotibial tract band
ITT	Intention-to-treat
KOOS	Knee injury and Osteoarthritis Outcome Score
KSS/AKSS	American Knee Society Scoring System
LCSmb	Low Contact Stress mobile bearing (Depuy)
LCSrp	Low Contact Stress rotating platform (Depuy)
LPS	NexGen® Legacy Posterior-Stabilised (Zimmer)

MC	Professor Matthew Costa
MF	Multiplication Factor
MFe	Miguel Fernandez (ACF ST3 Orthopaedic Trainee)
MJ	Michelle Joseph (Thesis author)
MPA	Mega Pascals
MPFL	Medial patellofemoral ligament
MR	multi-radius femoral component design
MRI	Magnetic Resonance Imaging
MUA	Manipulation under anaesthesia
OAA	onlay, asymmetrical, anatomical
OAP	onlay, asymmetrical, patient-specific
OKS	Oxford Knee Score
OSN	onlay, symmetrical, non-anatomical
PCL	Posterior Cruciate Ligament
PFA	Patellofemoral Arthroplasty
PFC	Press Fit Condylar (Depuy)
PMMA	poly methyl methacrylate
PP	Per-protocol
PS-TKA	Posterior stabilising Total Knee Arthroplasty
PSI	Pounds per square inch
QUOROM	Quality of Reporting of Meta-analyses
REC	Research Ethics Committee
RF	Rectus femoris
ROM	Range of Motion
SAEs	Serious Adverse Events
SAP	Statistical Analysis Plan
SOPs	Standard Operating Procedures
SR	single radius femoral component design
TC	Total Condylar (Howmedica)
TCP II	Total Condylar Prosthesis II (Zimmer)
THR	Total Hip Replacement
TKA	Total Knee Arthroplasty

TMG	Trial Management Group
TSC	Trial Steering Committee
UCLA Score	University of California, Los Angeles Physical Activity Score
UHMWPE	Ultra high molecular weight polyethylene
VAS	Visual Analogue Score
VI	Vastus intermedius
VL	Vastus lateralis
VLO	Vastus lateralis obliquus
VM	Vastus medialis
VMO	Vastus medialis obliquus
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index

Chapter 1 Introduction

1.1 Patellofemoral Arthritis

1.1.1 Definition, Incidence, Aetiology and Demographics

Isolated patellofemoral arthritis is a degenerative disease confined to the knee cap joint. In severe cases it is highly debilitating, manifesting in extreme pain particularly on rising from a chair and stair-climbing. This disorder affects a considerable number of patients and has a significant impact on quality of life (Duncan *et al.*, 2009).

A hospital-based study (Ledingham *et al.*, 1993) of patients referred with knee arthritis and a community-based study (Duncan *et al.*, 2006) of adults with knee pain both found the radiological prevalence of this disease to be 24%. A cross-sectional radiographic study performed by McAlindon *et al*. (1992) found 11% of men and 24% of women, over the age of 55 years, had isolated patellofemoral arthritis of which 2% and 8% of these men and women were symptomatic, respectively. Conversely, a radiographic study (Lacey *et al.*, 2008) carried out on a similar age group of symptomatic patients, reported a higher prevalence of symptomatic patellofemoral arthritis in the male population. This study reported 34.8% prevalence in men age 50 to 64 years compared to 18.5% in the equivalent female population. This disparity in prevalence between genders was not evident in the over 65 years group in which 23.9% of men and 20.9% of women had isolated patellofemoral arthritis.

A higher prevalence in men has not been shown in previous studies (Duncan *et al.*, 2006; Ledingham *et al.*, 1993; McAlindon *et al.*, 1992). Lacey *et al*. (2008) suggests occupational exposure may in part explain this difference. However, there is little evidence on lifetime occupational exposure to support this possible theory. In addition, the co-existence of other painful, non-articular diseases may lead to an underestimate of the presence of symptomatic patellofemoral arthritis in the associated female population. Furthermore, a number of studies have reported that the prevalence of patellofemoral arthritis is higher in women than men (Arendt, 2006; Dejour & Allain, 2004; Mihalko *et al.*, 2007; Saleh *et al.*, 2005). Other causal factors such as selective non-participation bias may explain the difference in prevalence between genders in this particular North Staffordshire population. At present, there is still more evidence suggesting patellofemoral arthritis is more common in women.

Our current understanding of aetiological factors associated with isolated patellofemoral arthritis is limited. Previous research has focused primarily on the tibiofemoral joint and has shown the development and progression of tibiofemoral osteoarthritis to be multifactorial. Such factors include age, trauma, gender and obesity, but it appears that not all these findings are applicable to the patellofemoral joint. The average age of those affected tends to be significantly lower than those with severe generalised arthritis (Davies *et al.*, 2002). A cross-sectional study (Tamm *et al.*, 2008) showed an association between increased body mass index

and tibiofemoral osteoarthritis but not patellofemoral arthritis. The same study also identified that early knee trauma strongly correlated with patellofemoral arthritis; this association was not present in the tibiofemoral osteoarthritis group. An earlier study (Cicuttini *et al.*, 1997) found an inverse relationship between premenopausal status and patellofemoral arthritis, not seen in patients with tibiofemoral osteoarthritis. In addition, histological and biomechanical human and animal studies have shown disparity in the patterns of patellofemoral arthritis disease progression (Clark, 2008) and in the volume of the articular cartilage of the patellofemoral joint compared to the tibiofemoral joint (Teichtahl *et al.*, 2006). These differences, coupled with the inherent complexities of the patellofemoral joint, suggest that the aetiological factors for development of patellofemoral arthritis may differ from those associated with tibiofemoral osteoarthritis or generalised knee osteoarthritis. Dejour *et al.* (2010) found idiopathic (primary) patellofemoral arthritis occurs in 49% of patients presenting with patellofemoral arthritis. Under 10% of patients will have suffered trauma to the patella and develop post-traumatic arthritis and a similar number will have chrondrocalcinosis. One third of patients develop patellofemoral arthritis as a result of patellar instability. These patients give a clear history of objective patellar dislocation.

Patellar instability secondary to misalignment of the patellofemoral joint or congenital trochlear dysplasia has been recognised as a risk factor for the development of patellofemoral arthritis (Mäenpää & Lehto,

1997b). Previous studies have reported between 4% and 70% development rate of patellofemoral arthritis following operative treatment for patellar instability (Nomura *et al.*, 2007; Sillanpää *et al.*, 2008). Sillanpää *et al*. (2010) detected evidence of patellofemoral arthritis in 78% of patients who had undergone non-anatomical procedures (Goldthwaite and Krogius) between 10 and 21 years prior to follow-up. The defects were most commonly seen in the medial facet and may therefore be a direct consequence of the operative procedure. Non-operative long-term outcomes have been reported by a small number of studies. Cofield and Bryan (1977) and Mäenpää and Lehto (1997a) published the outcomes of 50 and 100 non-operatively managed patellar dislocations with average follow-up times of 10 and 13 years, respectively. Both studies concluded better outcomes were achieved following non-operative management compared with non-anatomical operative management, although the latter methods of treatment are seldom used in current practice. Further research is required to identify the long-term effects of anatomical operative management, such as trochleoplasty (Schottle & Weiler, 2007) on the preservation of patellofemoral cartilage and thus progression to patellofemoral arthritis.

Patients with patellofemoral arthritis tend to present with anterior knee pain. Often this pain is exacerbated by prolonged flexion or descending stairs. Many anatomical abnormalities can result in patellofemoral disorders, these range from pelvic geometry anomalies, femoral anteversion or tibial torsion to increased varus/valgus angles at

the knee joint; all of which alter the mechanical axes of the lower limb and lead to abnormal alignment and contact pressures at the patellofemoral joint. Variations in the Q angle (intersection of two lines: tibial tubercle to patella and anterior superior iliac spine to patella) have been reported as having significant importance in the development of patellar instability and progression to patellofemoral arthritis (Mihalko *et al.*, 2007). Normal Q angles have been reported as ranging between 8° to 14° for males and 10° and 20° for females (Aglietti *et al.*, 1983; Freeman, 1987). Hughston (1968) advised any Q angle greater than 10° requires corrective surgery. Although this approach is quite aggressive the principle theory is very relevant. An increased Q angle can result in increased valgus force on the patella and consequential subluxation of the patella and increased compression forces on the lateral facet. Other abnormalities such as atrophied vastus medialis muscle and patella alta can also contribute to the development of patellofemoral arthritis.

Once the diagnosis of symptomatic patellofemoral arthritis has been established treatment is required to provide maximum pain control and minimise disability. The treatment offered is dependent on disease severity, patient age, co-morbidity and expectations. A number of non-operative and operative treatment modalities have been described for isolated patellofemoral arthritis (van Jonbergen *et al.*, 2010a). However, in the presence of severe disease the efficacy of non-operative treatments is limited. Interventions such as physiotherapy, taping and intra-articular injections/visco-supplementations offer only short-term

relief (Clarke *et al*., 2005; Cushnaghan *et al*., 1994; Quilty *et al*., 2003). Therefore operative treatment may be the only effective option. Surgical treatment of patellofemoral arthritis has included arthroscopic debridement, total or partial patellectomy and tibial tubercle osteotomies (Heatley *et al.*, 1986; Jenny *et al.*, 1996; Schepsis *et al.*, 1994) but with limited success. Arthroscopic surgery is seldom beneficial in severe disease and patellectomy often leads to poor long-term function due to weakness of the extensor mechanism (Lennox *et al.*, 1994). Total knee arthroplasty (TKA) and more recently, patellofemoral arthroplasty (PFA) have all been indicated. Total knee arthroplasty (TKA) is effective (Dalury, 2005; Laskin & van Steijn, 1999; Mont *et al.*, 2002; Parvizi *et al.*, 2001) but in a younger, more active patient is highly likely to require at least one revision. Patellofemoral arthroplasty (PFA) removes less bone, preserves near normal knee kinematics, and should be much simpler to revise. Therefore in these patients the definitive management choice is usually between TKA and PFA.

1.1.2 Patellofemoral Arthroplasty and Total Knee Arthroplasty

Although more recent studies have shown improvements in survivorship, the use of PFA has been associated with higher failure rates than TKA since its inception. Problems with understanding the indications and with the actual prosthetic designs are both partly to blame. Despite the advances made in both areas, a recent report from the National Joint

Registry for England and Wales (NJR) suggests the revision rate of PFA is almost four times that of TKA at three years (Wales, 2012). Furthermore, recent analysis of NJR data, over a seven year period, found unexplained pain to be the main cause of early revision, occurring in 46%, and not disease progression which was reported in only 14% of cases (Baker *et al.*, 2012). The cause of the pain, however, could not be determined from the registry data. Pre-existing tibiofemoral joint degeneration may have been the cause in a number of cases in light of the evidence published by Williams *et al*. (2013). This study suggests that a number of failures occurred as a direct result of ignoring these early tibiofemoral changes. The findings from both studies (Baker *et al.*, 2012; Williams *et al.*, 2013) strengthen the argument that PFA surgery should be carried out in specialist centres allowing a select number of surgeons to develop greater knowledge and skills in managing PFA patients. These concerns and the fact that PFA has been steadily gaining popularity over the last decade, suggest a systematic review of the outcomes associated with this type of prosthesis would be beneficial.

1.1.2.1 Design and Categorisation of Patellofemoral Arthroplasty

Poor results with early PFA were attributed to poor patient selection, prosthetic design, and failure to correct abnormal patellofemoral biomechanics.

Prosthetic design has evolved significantly over the last three decades. The early prostheses, which were predominantly inlay designs,

were associated with poor alignment (Blazina *et al.*, 1979; Tauro *et al.*, 2001). Better understanding of the biomechanics led to considerable changes in prosthetic design in the late 1980's to 1990's. This may have resulted in superior clinical outcomes (Ackroyd *et al.*, 2007; Odumenya *et al.*, 2010) although this association in terms of prosthetic design and outcome has not been formerly assessed. Recent designs have focused on recreating a more anatomical appearance, however the theoretical advantage of this feature is not reflected in recent evidence (Wales, 2012).

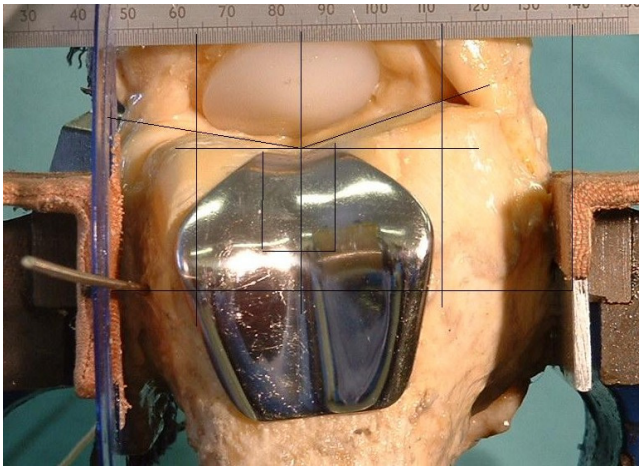
One of the challenges in patellofemoral prosthesis design is balancing constraint and congruence. Critical characteristics of trochlear component geometry include the level of constraint, medial-lateral width, thickness, distal sagittal arc of curvature, and proximal extension of the anterior flange.

The main differences between the early and newer PFAs were changes to the geometry of the trochlear component. The early prostheses were typically inlaid into the trochlea, generally had a smaller surface area, length and width, and a deeper, more constraining trochlear groove (Figure 1-1A-B). The principle of the inlay design was to prevent overstuffing the patellofemoral joint. However, such a deep central groove required more bone resection. Conversely, the later trochlear components are mainly onlay designs and are wider (Figure 1-1C-F). The aim is to restore normal trochlear offset. By restoring the offset the soft

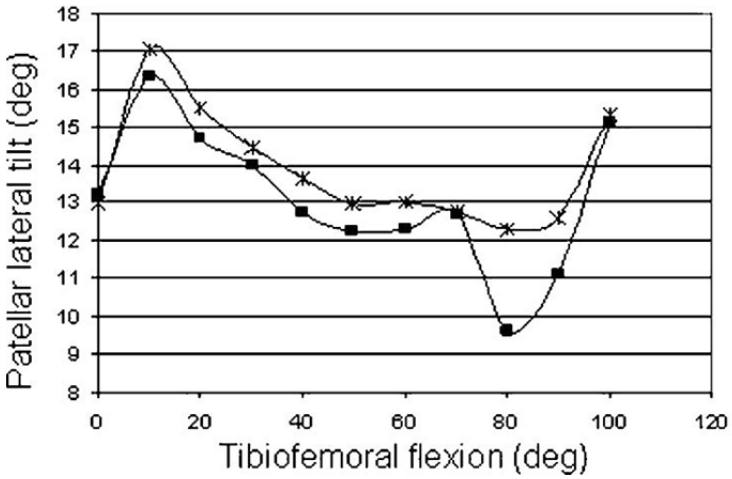
tissue tensions and the mechanical advantage of the extensor mechanism can be normalised.

Figure 1-1 A-G [A] Lubinus, [B] Richards III, [C] Avon, [D] FPV, [E] Journey, [F] Zimmer Gender Solution, [G] Arthrosurface HemiCAP® WAVE

Unlike the inlay design, the positioning of the onlay device is not completely determined by the geometry of the native trochlea. Rather, the trochlear component may be implanted in an orientation decided by the surgeon, to improve tracking. In the presence of a hypoplastic lateral femoral condyle the component can be rotated into varus to prevent its distal lateral edge being too prominent. However, there may be a conflict between patellar tracking along the groove, versus the desire to avoid a step in the articular surface, and that may risk catching and clunking symptoms (Figure 1-2 A-B) (Amis *et al.*, 2005). In trochlear dysplasia, the groove is usually medialised; in some cases simple lateral placement of an onlay component will allow the correct coronal alignment without creating lateral prominence.



A



B

Figure 1-2 [A] An Avon prosthesis in-situ in-vitro is shown. [B] An example of an erratic tracking pattern for patellar tilt caused by the patella catching on the distal edge of the femoral component when the knee is extended is shown. The "X" marks represent knee flexion and the black squares represent knee extension. Permission to use image granted by copyright owners Lippincott Williams & Wilkins. Amis AA, Senavongse W, Darcy P. Biomechanics of patellofemoral joint prostheses. *Clin Orthop* 2005; 436:20-29.

The newer, onlay designs also have a longer anterior flange that extends proximally, ensuring that the patellar component remains in contact with the trochlear component in full knee extension (Figure 1-3 B). This avoids the need for the patella to negotiate a step in early knee flexion.

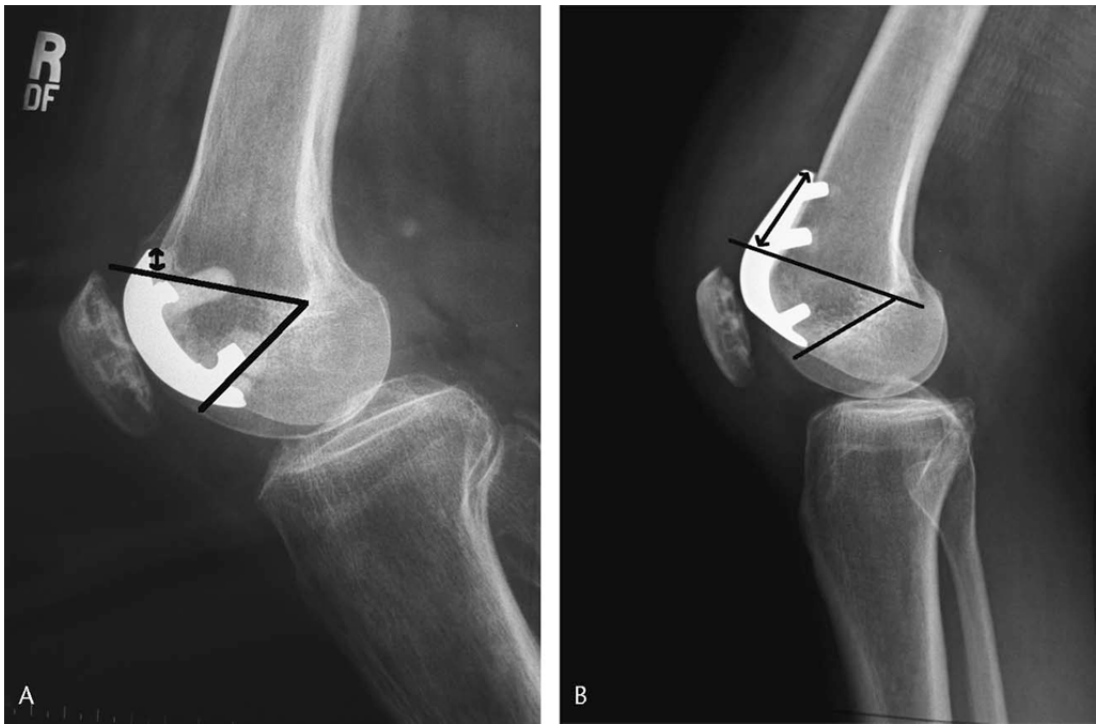


Figure 1-3 [A] The short anterior flange of the Lubinus prosthesis causes the patella to catch or sublux as it moves from the native femoral articular surface to the prosthesis in the initial 30° of knee flexion. [B] The Avon prosthesis has a much longer proximal extension of the anterior flange ensuring the patellar component remains in articulation with the trochlear component in full extension.

Permission to use image granted by copyright owners Lippincott Williams & Wilkins. Lonner JH, Patellofemoral arthroplasty: pros, cons and design considerations. *Clin Orthop* 2004; 428:158-165.

Prostheses have been classified by 'generation' but this is not helpful as it defines by date of inception and gives no indication of design. An alternative, more useful approach is to initially categorise by design principles such as inlay/onlay, symmetrical/asymmetrical, non-anatomical/anatomical/patient-specific and secondarily by constraint within each category. Based on the available literature, practical experience with the prostheses and the description according to the manufacturers, six distinct groups have been established, shown in Table 1-1.

Table 1-1 Prosthesis Categorisation

Year of inception	Implant	Implant Design characteristics			
		Onlay/ Inlay	**Asymmetric/ Symmetric**	**Anatomical/ Non-anatomical**	**Constraint**
1974/76/84	Richards I, II, III	Inlay	Symmetric	Non-anatomical	Highly constrained
1975	Lubinus	Inlay	Asymmetric	Non-anatomical	Highly (S) Unconstrained (XL)
1976	CSF-Wright	Inlay	Symmetric	Non-anatomical	Unconstrained
1980	Autocentric I, II	Inlay	Asymmetric	Non-anatomical	Constrained
1987	Spherocentric	Inlay	Asymmetric	Non-anatomical	Constrained
1997	LCS	Inlay	Asymmetric	Anatomical	Highly constrained
1996	Avon	Onlay	Symmetric	Non-anatomical	Unconstrained
1997	Hermes	Onlay	Asymmetric	Anatomical	Semi-constrained
2004	Vanguard	Onlay	Asymmetric	Anatomical	Unconstrained
2008	Natural Knee II	Onlay	Asymmetric	Anatomical	Semi-constrained
1996	FPV	Onlay	Asymmetric	Anatomical	*Highly constrained
2005	Journey	Onlay	Asymmetric	Anatomical	Semi-constrained
2008	Zimmer	Onlay	Asymmetric	Anatomical	Semi-constrained
1994	Custom Performa Knee	Onlay	Asymmetric	Anatomical-patient specific	Semi-constrained
1995	Kinematch	Onlay	Asymmetric	Anatomical-patient specific	Semi-constrained

This table lists the prostheses in terms of design categorisation: inlay or onlay, asymmetric or symmetric, non-anatomical or anatomical and degree of constraint. The earlier prostheses were mainly inlay, asymmetric designs with variable constraint. The more recent designs are onlay, asymmetrical, anatomical and semi-constrained.

*** The FPV patellar component is multifacetted, creating a highly constrained prosthetic joint. In contrast, the FPV femoral component has a wide sulcus angle and is less constraining when combined with an axisymmetric patellar button.**

1.1.3 Current Clinical and Biomechanical Issues with Arthroplasty Treatment

Whilst some surgeons consider TKA the gold standard, providing good function and low revision rates (Dalury, 2005; Laskin & van Steijn, 1999; Mont *et al.*, 2002; Parvizi *et al.*, 2001; Thompson *et al.*, 2001), others believe PFA is a better treatment as it preserves healthy bone and native

soft tissue restraints and offers an easier operative environment should revision surgery to TKA be required (Argenson *et al.*, 2005; Cartier *et al.*, 2005; Lonner *et al.*, 2006; Merchant, 2004; Sisto & Sarin, 2006). Although the majority of surgeons are aware of the advantages of both types of arthroplasty, the decision regarding which procedure to perform is often a difficult one in the absence of a consensus.

1.1.3.1 Clinical Issues

The main clinical issues resulting in this lack of consensus lie in the differences in opinion regarding indications and contraindications, which ultimately impacts functional, survival and complication outcomes. Some surgeons advocate PFA should be reserved for patients with isolated severe patellofemoral arthritis secondary to trochlear dysplasia, a prior patellar fracture and those with a near neutral Q angle (Argenson *et al.*, 2005; Cartier *et al.*, 2005; Nicol *et al.*, 2006). Argenson *et al*. (2005) reported a disproportionate number of patients with idiopathic patellofemoral arthritis experienced disease progression (tibiofemoral osteoarthritis) compared with those who had a history of patellar dislocation or trauma to the patella. Nicol *et al*. (2006) reported 0% disease progression in all patients with trochlear dysplasia at seven years compared with a 16% rate in those with primary patellofemoral arthritis. Although these findings are convincing, other authors have reported results in groups of patients with idiopathic patellofemoral arthritis that are comparable to those seen in patients with trochlear dysplasia (Merchant,

2005; Sisto & Sarin, 2006). Anatomical variant, patella baja (low lying patella) is a recognised contraindication for PFA.

There is little consensus on the most appropriate age group to whom PFA surgery should be offered. Sisto & Sarin (2006) chose not to perform PFA in any patient over the age of 55 years. They took the view of PFA being temporary surgery rather than definitive. On the contrary, some advocate PFA to be a suitable operation for elderly patients who are unlikely to develop disease progression during the remainder of their lives. While others argue that young active patients should receive TKA as this operation near guarantees improvement in symptoms and return to activities of daily living and avoids the risk of disease progression (Diduch *et al.*, 1997).

This broad variation in whom best to offer PFA surgery cannot be determined from systematically reviewing the literature due to the current level of evidence available (predominantly retrospective uncontrolled case series'). However, a systematic review to first ascertain the survival and complications outcomes following PFA and TKA by design differences may inform the choice debate. The definitive study is a randomised clinical trial comparing PFA with TKA, assessing function, prosthesis survival and complication outcomes.

1.1.3.2 Biomechanical Issues

The main biomechanical challenges with TKA and PFA are restoring knee kinematics whilst maintaining extensor mechanism integrity. The

integrity of the knee extensor mechanism is crucial for the performance of daily activities such as rising from a chair, normal walking and stair climbing. Existing literature describes the effects on the extensor mechanism following TKA but fall shorts of providing any data on the effects following PFA. Patients who have undergone TKA surgery tend to rise from a chair more slowly compared with those without knee pathology and also tend to rely on the unaffected leg (Mizner *et al.*, 2005).

Quadriceps strength insufficiency can remain for a number of years after TKA, as demonstrated by Huang *et al*. (1996). In this study, the authors compared posterior cruciate retaining and sacrificing prostheses and found no significant difference between them in terms of hamstring to quadriceps ratio. When compared with healthy individuals this measurement was found to be higher in patients who had undergone arthroplasty (between six and thirteen years ago). Potential reasons for this include disuse atrophy due to low pre- and post-operative activity in order to preserve prosthesis survivorship. Secondly, during the experiments some patients did not exhibit maximal performance out of fear that their TKA may fail under extreme exertion and thirdly, anterior cruciate deficient knees generally have a lower level of quadriceps strength with no effect on hamstring strength (Kannus, 1988).

Decreased walking and stair climbing speed have also been reported as indicators of quadriceps weakness by Walsh *et al*. (1998); a finding further supported by more recent studies (Mizner *et al.*, 2005;

Mizner & Snyder-Mackler, 2005). Prosthetic design has the potential to enhance this weakness or improve the efficiency of the extensor mechanism.

Traditionally, knee flexion and extension were thought to occur around changing instant centres of rotation, this theory resulted in the design of multi-radius knee prostheses. However, Huang *et al*. (1996) reported that these designs do not restore the extensor mechanism moment arm to normal. The current belief is that there is a single, fixed flexion-extension axis located near the transepicondylar axis (Churchill *et al.*, 1998). In theory, this relatively more posterior (single radius) axis of rotation (compared with that of the multi-radius TKA) lengthens the extensor mechanism moment arm and results in a better functioning extensor mechanism. This improved function is theoretically due to the inverse effect that increase in quadriceps moment arm has on quadriceps force, that is, less force is required at higher quadriceps moment arms for knee extension to occur. The overall effect is improved efficiency of the extensor mechanism (Mahoney *et al.*, 2002). There are two types of TKA that allow for this theoretical posterior displacement: posterior cruciate retaining (CR-TKA) and posterior cruciate substituting/stabilising (PS-TKA). Posterior sacrificing designs are no longer popular as in the absence of both cruciate ligaments anterior displacement occurs, which is firstly non-anatomical and secondly shortens the moment arm thus decreasing the efficiency of the extensor mechanism. Bolanos *et al*. (1998) found no difference in flexion moments during level walking or

stair climbing between substituting and retaining compared to Dorr *et al*. (1988) who compared sacrificing with retaining. This difference may be due to the PS-TKA having a cam mechanism to substitute for the function of the posterior cruciate ligament and thus allowing rollback of the femoral component on the tibial component during knee flexion. This prosthesis permits a wider range of motion compared with a cruciate-sacrificing prosthesis and is theoretically mechanically beneficial for the quadriceps muscle, potentially promoting increased quadriceps strength (Insall *et al.*, 1982; Scuderi & Insall, 1992). Critical appraisal of these studies along with other relevant literature is required to determine the plausibility of these conclusions.

Previous studies assessing extensor mechanism function following single radius versus multi-radius TKA have shown varied outcomes. Studies evaluating PS-TKA have reported single radius PS-TKA as superior (Gomez-Barrena *et al.*, 2010; Mahoney *et al.*, 2002). Conversely, other investigations assessing CR-TKA found no difference between single and multi-radius (Hall *et al.*, 2008). Currently, there are no review articles or randomised trials to determine whether single radius is mechanically more favourable than multi-radius for CR-TKA or PS-TKA femoral designs.

More recent literature has focused on comparing the migration of tibial components following single radius CR-TKA and PS-TKA or stability of single radius versus multi-radius CR-TKA (Jo *et al.*, 2014; Molt & Toksvig-Larsen, 2014) rather than directly comparing CR- and PS-TKA

with regards to the effects on extensor mechanism. Efficiency of the extensor mechanism following PFA has not been assessed. The extensor mechanism is the primary support of the knee during standing and walking. In light of this importance, it is imperative to identify which type of arthroplasty provides the most efficient extensor mechanism. This information may influence the decision to perform TKA or PFA in future patients with isolated patellofemoral arthritis.

1.2 Rationale for PhD

Analysis of knee arthroplasty through objective and subjective assessment has brought to light important information for the orthopaedic community (Dawson *et al.*, 1998; Ewald, 1989; Insall *et al.*, 1976; Murray *et al.*, 2014). Conventionally, a clinical review of a patient following TKA or PFA consists of radiographs and clinical outcomes. These outcomes are used to evaluate function, complications and implant survival. This data is vital for determining such factors on a pragmatic level but limited in providing any inference regarding prosthetic design or specific muscle efficiency. Investigating the influence of TKA and PFA design on extensor performance is important for the future development of these interventions. It is for these reasons the focus of this thesis was on both the clinical and biomechanical aspects of TKA and PFA.

To date there are no published randomised clinical trials comparing TKA with PFA for the treatment of severe isolated PFOA. The use of PFA is now rapidly increasing and it is therefore extremely important to determine both for the NHS and patient welfare, whether this procedure offers better knee function than TKA. Performing such a study would also provide data to support a larger multicentre trial.

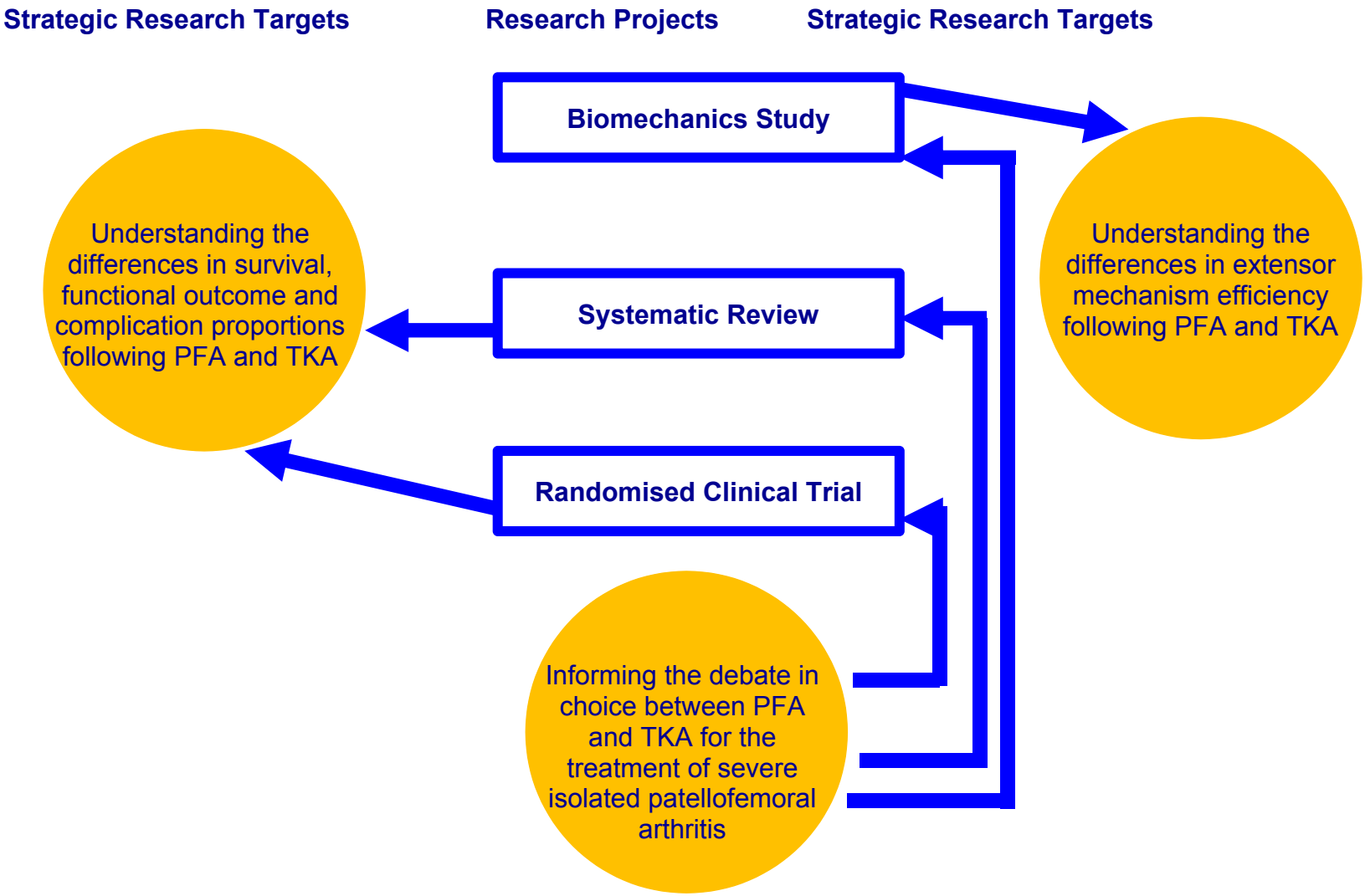
One meta-analysis reported on the complications of PFA compared with TKA (Dy *et al*., 2012). However, the prostheses were grouped based on time of inception rather than component design. Furthermore, the heterogeneity that exists within these groups is high and therefore the appropriateness of performing a meta-analysis is questionable. A more, meaningful approach would be to assess the survival and complication proportions associated with prosthetic designs.

1.2.1 Research Objectives

The overall aim of this thesis is to inform the PFA versus TKA debate by determining the differences in extensor mechanism efficiency, survival, functional and complication outcomes following TKA and PFA treatment for severe isolated patellofemoral arthritis. This will be achieved by completing the following thesis objectives:

1. To conduct a comparative cadaveric biomechanical study to determine the differences in extensor mechanism efficiency following TKA and PFA.
2. To systematically review the survival and complication proportions following TKA and PFA (using the design categorisation system) for severe isolated patellofemoral arthritis.
3. To perform a pragmatic randomised clinical trial to identify whether a difference exists between TKA and PFA in terms of functional outcomes for severe isolated patellofemoral arthritis.

1.2.2 Targets for Research



1.2.3 Potential Impact

The potential impact of this research is to further inform the debate regarding the use of PFA and TKA for severe isolated patellofemoral arthritis. The biomechanics study could act as the benchmark to more translational studies. The systematic review will act as a good reference for determining what the literature advises on the use of both treatment modalities. The randomised clinical trial will offer unbiased results on the functional outcome of both treatments, which until now has not been available.

Chapter 2 Extensor Mechanism Efficiency Following Patellofemoral Arthroplasty and Total Knee Arthroplasty

2.1 Abstract

Objectives

Extensor mechanism weakness following TKA is a recognised phenomenon. However, the effect on quadriceps function following PFA has not been evaluated. The purpose of this study was to first establish a broad overview of the literature related to prosthetic design and extensor mechanism function through carrying out a narrative literature review and secondly perform an experimental cadaveric study assessing the effect of geometrical differences between PFA and TKA on extensor mechanism efficiency, patellofemoral resultant force, peak pressure and contact area.

Methods

Eight fresh frozen cadaveric knees were mounted in a kinematic rig. Constant load was applied to the quadriceps muscles and ITB. Each knee was subject to four conditions: native knee, Zimmer PFA, CR-TKA and PS-TKA. Repeated measures of all four parameters were performed under each condition for all eight knees. Extensor mechanism efficiency was measured from 120° to 0° at 10° increments using a calibrated strain gauge device connected to the rig. The other three parameters were measured using Tekscan sensors placed between the patella and trochlea. Analysis was performed using one-way ANOVA and post-hoc paired *t*-test with a corrected significance level of $p < 0.00833$.

Results

The results show extensor mechanism efficiency was significantly greater for PFA between mid flexion to full extension (50° to 0°) when compared with the native knee, CR-TKA and PS-TKA. The reverse occurred in deep flexion, although the differences between the arthroplasty conditions were not significant. No difference in resultant force was detected between the arthroplasty conditions. A significant reduction in PFA peak pressure in deep flexion (90° and 120°) corresponded with increased contact area as the patellar button came into articulation with the native femoral condyle. High peak pressures greater than four times that measured in the native knee were detected in all three arthroplasty conditions at 0°.

Conclusion

Despite previous reports in the literature, no difference in any of the parameters was found between CR-TKA and PS-TKA. The greatest extensor mechanism efficiency was produced by PFA in mid flexion to full extension. Further work is required to determine whether this increased efficiency provides benefit during the performance of ADLs such as walking. The methodology of this study will provide the benchmark for such future translational research.

2.2 Literature Review: The Effects on the Extensor Mechanism following Patellofemoral Arthroplasty and Total Knee Arthroplasty

2.2.1 Introduction

The integrity of the knee extensor mechanism is the most important factor that determines a patient's ability to climb stairs or rise from a chair. These movements, along with normal walking, are an integral part of daily living, which if compromised, can be highly debilitating. This problem is not uncommon following total knee arthroplasty (TKA).

There is much controversy associated with the use of TKA and patellofemoral arthroplasty (PFA) for the treatment of isolated patellofemoral arthritis. Current literature focuses on differences in clinical functional outcome; the difference in extensor mechanism function between the two prostheses remains unknown.

The aim of this narrative literature review was to address the broader issues related to knee extensor mechanism function following PFA and TKA through achieving the following objectives:

1. To summarise the relevant anatomy of the patellofemoral joint
2. To summarise the biomechanics of the knee extensor mechanism, abnormal patellofemoral biomechanics and biomechanics related to PFA

3. To determine the clinical importance of quadriceps weakness following knee arthroplasty
4. To determine the impact of TKA prosthetic design in terms of cruciate retaining, sacrificing or substituting on extensor mechanism function
5. To determine the impact of TKA prosthetic design in terms of femoral component radii: multi-radius versus single radius on extensor mechanism function
6. To propose theoretical extensor mechanism function following PFA

For each of the objectives the relevant literature was identified impartially. Although not a systematic review by definition, efforts were made to reduce bias by using established search databases, such as Medline and EMBASE. Search terms used were applicable to the specific objectives stated above. Relevant peer-reviewed studies in English were included. Synthesis of the literature and evaluation of the strength of the evidence provided the necessary information to make an informed judgement about how to design and rationalise the methodology of the subsequent experimental study.

2.2.2 Anatomy of the Knee Extensor Mechanism

The patella, the largest sesamoid bone, has the thickest articular cartilage found in the body. It has seven articular facets: the medial and lateral

facets, which are both divided into equal third sections and the most medial portion called the odd facet. Throughout the entire flexion-extension cycle, some aspect of the patellar articular surface is loaded with the exception of the earliest degrees of knee flexion (Grelsamer & Weinstein, 2001). The patellofemoral contact surface area in the native knee is illustrated in Figure 2-1; Table 2-1 describes the articular location of this contact on both joint surfaces.

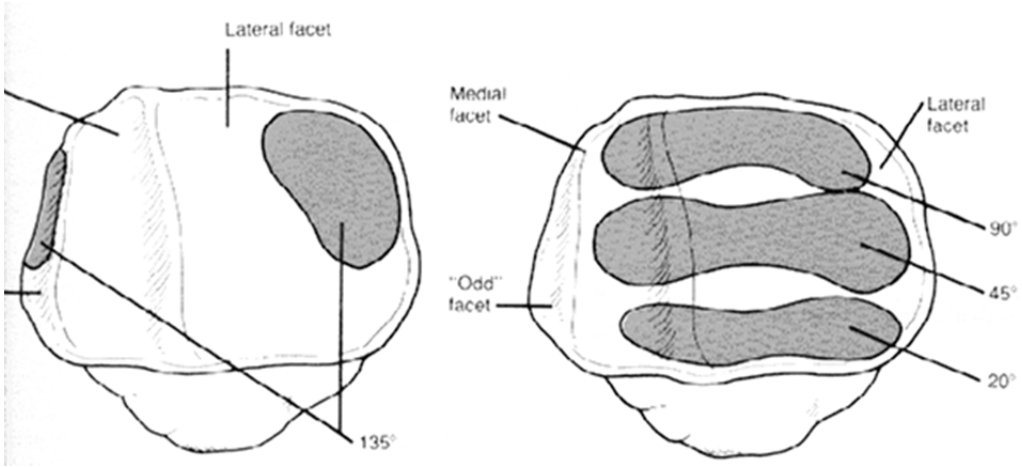


Figure 2-1 Patellofemoral Contact Areas at knee flexion angles (Goodfellow *et al.*, 1976)

Table 2-1 Patellofemoral Joint Contact Surface Locations

Flexion angle	Patella articulation	Femoral articulation
0°	Minimal bony contact	Femoral sulcus
20°-30°	Inferior facet	Middle femoral sulcus
60°	Middle facets	Superior femoral notch
90°	Middle and superior lateral facets	Superior femoral notch
120°	Lateral middle and superior facets	Superior femoral notch and lateral femoral condyle
135°	Lateral middle, lateral superior and odd facets	Lateral femoral condyle and lateral surface of medial femoral condyle

Contact between the patella and trochlea that covers a larger surface area will distribute the load over a greater area. At 30° knee flexion, the area of patellofemoral contact is approximately 20mm^2 in the native knee.

The area of contact gradually increases as the knee is flexed. At 90° of knee flexion contact area triples, increasing up to 60mm^2. The contact area increases in size as the patellofemoral joint becomes more congruent. The motion of the patella and hence maintenance of this congruency is largely dependent on the soft tissue constraints of the joint.

The patella acts as a central point of attachment for the extensor ligaments and tendons and therefore governs the alignment of the entire extensor mechanism. The most proximal aspect of the patella is extra-articular and lies within the quadriceps tendon. The articular surface extends from the quadriceps tendon to the inferior pole of the patella.

The extensor mechanism consists of three distinct, convergent layers that insert into the proximal patella. The superficial layer is comprised of the rectus femoris muscle, which constitutes approximately 15% of the cross-section of the extensor mass (Clarke *et al.*, 2001). This muscle originates from the ilium as two heads, which unite to form one muscle that travels distally in the anterior thigh. Approximately 5 to 8cm proximal to the superior pole of the patella the muscle tapers and become tendinous (Reider *et al.*, 1981). These fibres pass onto the anterior aspect of the patella and become continuous with the patellar tendon. Beneath lie the vasti lateralis (VL) and medialis (VM) in the intermediate layer, which converge to form a tendinous structure holding the patella in a central position. The VL originates at the proximal part of the trochanteric line and runs to the midpoint of the linea aspera. The distal margin of fibrous tissue merges with the lateral patellar retinaculum,

attaching to the tibia. The VM originates from the distal aspect of the trochanteric line and extends to the distal medial portion of the linea aspera; the most distal fibres arise from the adductor magnus tendon and insert into the quadriceps tendon. The deepest layer contains the vastus intermedius, which originates from the anterolateral aspect of the femoral shaft and is covered anteriorly by an aponeurosis that is continuous with the quadriceps tendon. All three layers unite as the quadriceps tendon and for this reason the tendon is often described as having a trilaminar structure, although in reality the structure is more complex (Reider *et al.*, 1981).

Both VL and VM have distinct oblique heads formed from distal fibres that insert into respective patellar retinaculae. The vastus medialis obliquus (VMO) inserts at an angle approximately 50° to the femoral axis (Lieb & Perry, 1968) allowing it to function effectively as an active medial-lateral stabiliser; it is not involved in knee extension. This is equally true for the vastus lateralis obliquus (VLO) acting on the opposing side (Amis & Farahmand, 1996). The dynamic equilibrium between these structures, aided by the effective angles of insertion, allows for maintenance of medial-lateral balance and patellar tracking. In addition to these active stabilisers, the retinacular structures, most importantly the medial patellofemoral ligament (MPFL), which attaches to the patella and under surface of the VMO and vastus intermedius aponeurosis, provide passive restraint against lateral patellar subluxation (Conlan *et al.*, 1993). The

lateral aponeurosis extends from the ilio-tibial band to the patella and in part opposes the action of the medial retinacular structures.

Distally, the quadriceps tendon attaches to the base and sides of the patella via an aponeurotic expansion anterior to the patella. This thin sheet continues distally and passes into the patellar tendon and medial and lateral patellar retinaculae. The patellar tendon is a strong, ligamentous structure connecting the inferior pole of the patella to the tibial tuberosity. The pull of the quadriceps tendon on the patellar tendon is not a straight line due to the inclination of the femoral shaft (defined as, a line adjoining the anterior superior iliac spine and the centre of the patella) and alignment of the tibial tuberosity (a line between the anterior, central aspect of the tibial tuberosity and centre of the patella). The axis of both tendinous structures crossing at the central aspect of the patella forms the Q angle, which dictates the direction of pull. The angle is always valgus with mean values of 14° in men and 17° in women (Aglietti *et al.*, 1983), which predisposes the patella to lateral displacement. However, the lateral slope of the femoral trochlea, VMO and medial retinaculum resist this movement.

2.2.3 Biomechanics of the Knee Extensor Mechanism

During level walking the forces across the tibiofemoral joint can reach five times body weight, although the peak during the gait cycle is usually between 2 and 4 times body weight (Morrison, 1970). The force across the patellofemoral joint during the same activity is of the order of half

body weight (Reilly & Martens, 1972). The precise level of loading depends on internal factors such as alignment between the femur and tibia and any residual deformity and external factors, such as the speed of walking and environmental conditions. Ascending and descending stairs has little effect on the tibiofemoral forces in contrast to those created at the patellofemoral joint. The force increases significantly in this joint, up to 1.5 to 2 times body weight on ascent and 2.5 to 3 times body weight on descent. This 3 to 6 fold increase in patellofemoral force is primarily due to the increased activity of the quadriceps. However, greater forces are exerted across the patellofemoral joint during rising from a chair unaided by arms. During this activity, the patellofemoral forces reach 3.5 times body weight (whereas tibiofemoral forces are 4 times body weight). More strenuous activities such as running, squatting and jumping will significantly increase the magnitude of these patellofemoral forces.

The knee extensor mechanism is essential for simple walking. Specifically, it is responsible for the propulsion action during the stance phase. The magnitude of the force created is primarily due to the quadriceps action resulting in knee extension and the gastrocnemius plantar flexing the foot, the overall effect being forward propulsion of the body.

The main role of the patella is to enhance the efficiency of the extensor mechanism through the following two biomechanical functions. Firstly, the patella displaces the patellar tendon anteriorly, away from the

surface of the femur, resulting in lengthening of the extensor moment arm. This effect becomes less significant when the knee is in deep flexion. In this position the patella is engaged in the intercondylar notch and only marginally displaces the quadriceps tendon anteriorly; and therefore has little effect on the extensor moment arm. Secondly, the patella increases the surface area over which the joint compressive forces are applied. The significance of the patella in increasing the length of the extension moment arm depends on the degree of knee flexion.

During terminal knee extension the patella disengages from the trochlea and is pulled laterally by the force of the vastus lateralis. Conversely, during the initial 30° of knee flexion the patella moves relatively medially and the lateral facets of both the patella and proximal trochlear groove engage. After which the patella travels along the trochlear groove, parallel to the mechanical axis of the femur in the coronal plane (Ahmed *et al.*, 1999; Amis *et al.*, 2006; Heegaard *et al.*, 1994; Nagamine *et al.*, 1995). Engagement of the patella is maintained as it passes into the distal portion of the trochlear groove in deep flexion. Here it bridges the femoral intercondylar notch and femoral rollback occurs.

2.2.3.1 Abnormal patellofemoral biomechanics and biomechanics related to patellofemoral arthroplasty

In patients with patellar maltracking lateral displacement of the patella can occur, the severity of which is dependent on the integrity of the surrounding soft tissue stabilisers and bony alignment. A trochlear component that engages the patella early, has a groove with sufficient depth and has adequate coverage when reaching the intercondylar notch, could prevent mild lateral subluxation. However, if the lateral facet of the trochlea is too prominent, it may lead to retinacular impingement and pain, creating a similar effect as the Albee procedure (Albee, 1915).

It is important to appropriately balance the soft tissues, recognising that a high proportion of cases have lateral misalignment with a tight lateral retinaculum related to longstanding trochlear dysplasia. This can be corrected in various ways, including lengthening of the retinaculum by a subperiosteal lateral peripatellar release (Ackroyd, 2005). The medial retinacular structures and medial patellofemoral ligament (MPFL) stretch over time, presenting a further problem for soft tissue balance. In some instances, MPFL reconstruction or, albeit rarely, tibial tuberosity anteromedialisation may be indicated (Dejour *et al.*, 1994; Schöttle *et al.*, 2005).

The mechanics of medial-lateral stability, rotation in the sagittal plane (flexion-extension) and rotation and translation in the coronal plane are of crucial importance (Rhoads *et al.*, 1990). During the initial 30° of tibiofemoral flexion there is a lag discrepancy between tibiofemoral flexion and patellar flexion due to the distal translation of the patella that occurs.

Beyond this, the patella rotates around the arc of the femoral articular geometry in the sagittal plane, with 55° of patellar flexion at 90° tibiofemoral flexion (Amis *et al.*, 2005). A femoral component with a low-profile would allow this motion to occur smoothly and thus avoid the 'catching' or 'snapping' symptoms caused by a bulky anterior flange that forces the patella into extension during initial engagement.

A previous study (Amis *et al.*, 2005) assessed the pre- and post-operative tracking kinematics *in vitro* of four different patellofemoral arthroplasties and found the Avon (Stryker) and Leicester (Corin Group, Cirencester, England) implants had tracking paths that most resembled the native knee (Figure 2-2). Unsurprisingly, the Richards (Smith & Nephew) (Blazina) had a comparatively linear pattern following engagement into the V-shaped trochlear groove. The Lubinus (Link Co.) demonstrated an inconsistent pattern in some of the specimens, most likely due to abrupt changes in patellar tilt occurring at the transition point between the trochlear component and the native femoral condyles.

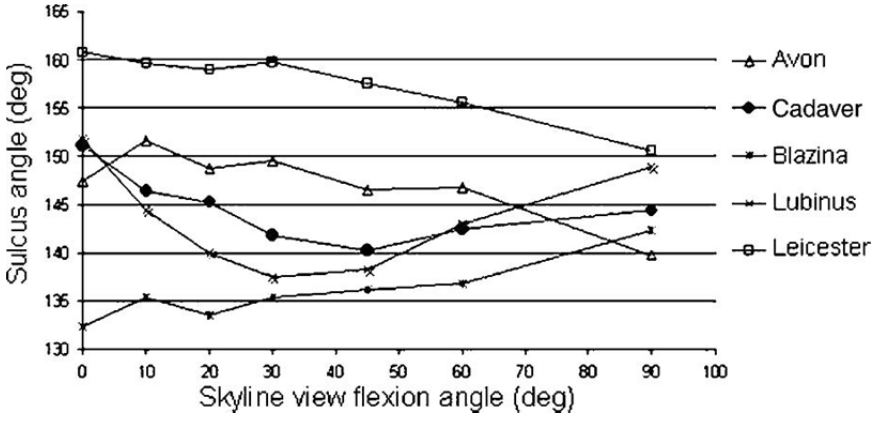


Figure 2-2 Variation of trochlear sulcus angle with flexion around femoral components and intact natural knees are shown. On the x-axis, 0° = view along femur and 90° = AP view. Permission to use image granted by copyright owners Lippincott Williams & Wilkins. Amis AA, Senavongse W, Darcy P. Biomechanics of patellofemoral joint prostheses. *Clin Orthop* 2005; 436:20-29.

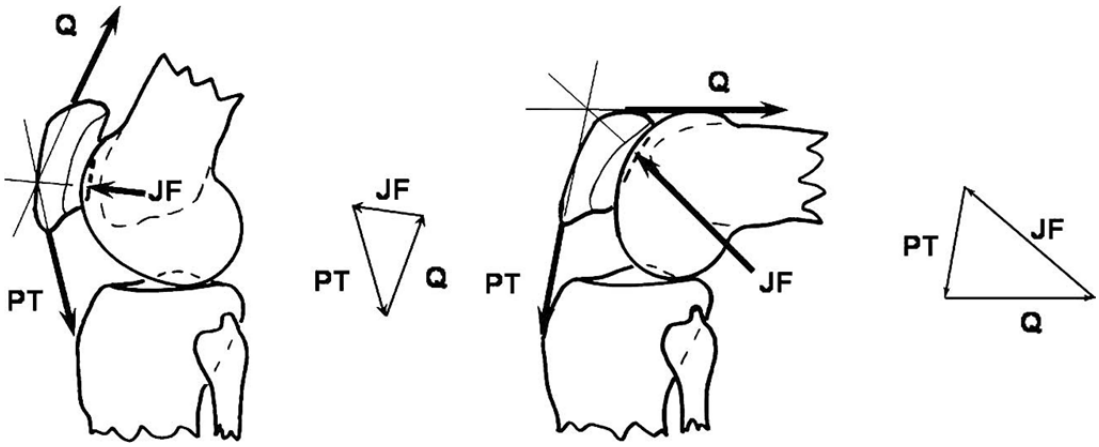


Figure 2-3 Forces acting on the patella in the sagittal plane. Quadriceps tension (Q), patellar tendon tension (PT) and joint force (JF). The JF moves proximally across the patella as the knee flexes, rising significantly with increase in knee flexion for the same PT. Permission to use image granted by copyright owners Lippincott Williams & Wilkins. Amis AA, Senavongse W, Darcy P. Biomechanics of patellofemoral joint prostheses. *Clin Orthop* 2005; 436:20-29.

Patellofemoral joint reaction forces occur as a result of the tension in the extensor mechanism. The force vectors in the sagittal plane are composed of the quadriceps and patellar tendon tensions (Figure 2-3). In the coronal plane this force has a dominant lateral component caused by the Q angle (Neumann, 2002). The compressive nature of the joint force suggests that loosening is unlikely, but the force moves across both the trochlea and patella during knee flexion, and so rocking micromotion must be resisted. As knee flexion increases the forces created are larger and move closer to the proximal edge of the patella. The native patella can accommodate such forces but the periphery of a patellar button consists of a flat skirt and therefore small contact areas are subjected to very high forces during daily activities (Table 2-2 (Andriacchi *et al.*, 1980; Boccardi *et al.*, 1981; Dahlkvist *et al.*, 1982; Ellis *et al.*, 1984; Ericson & Nisell, 1987; Huberti & Hayes, 1984; Kuster *et al.*, 1993; Matthews *et al.*, 1977;

Morrison, 1970; Nisell, 1985; Reilly & Martens, 1972; Winter, 1983) cited from (Kuster *et al.*, 1997).

Table 2-2 Reported patellofemoral joint loads for several daily activities

Author	**Activity**	**Patellofemoral joint load (Body weight multiples)**
Ericson	Cycling	1.2
Reilly and Martens	Level Walking	0.5
Matthews (Morrison)		0.7
Nisell (Boccardi)		1.3
Kuster		1.8
Nisell (Andriacchi)	Stair ascending	2.1
Reilly & Martens		3.3
Matthews (Morrison)		2.5
Nisell (Andriacchi)	Stair descending	5.6
Reilly & Martens		3.3
Matthews (Morrison)		2.5
Matthews (Morrison)	Downhill walking	1.8
Kuster		7.0
Ellis	Rising from a chair	3.1
Nisell (Winter)	Jogging	7.0
Dahlkvist	Squat descent	7.6
Huberti	Isometric contraction at 90° flexion	6.5

NB: The data for the joint load calculations taken from secondary sources are indicated in the parentheses. Reproduced with permission and copyright © of the British Editorial Society of Bone and Joint Surgery (Kuster *et al*., 1997).

It is believed that fibrous tissue forms around the patella and buffers some of this load (Cameron & Cameron, 1987). For this reason some surgeons advocate using a smaller patellar component, leaving a bony rim of cancellous surface around the button to allow this ‘patellar meniscus’ to form. Numerous fixation pegs cemented into the patellar bone may resist potential rocking/loosening displacement of the

component. A previous study found an increased rate of patellar fracture associated with one-peg compared with three-peg patellar component design (Larson *et al.*, 2001). Earlier, Gioir *et al.* (1990) established that the stability of a prosthesis subjected to shear forces is in part dependent on the number, size (length/diameter ratio) and positioning/proximity of the peg fixations; a prosthesis with multiple small pegs that has the same shear yield value as a prosthesis with fewer, larger pegs will have a stiffer shear fixation as smaller pegs offer more shear stability per unit volume.

In the native knee the trochlea is asymmetrical. The lateral articular facet is approximately 50% larger than the medial to accommodate the higher load. This arises because, although the trochlea is aligned to the femoral mechanical axis (Iranpour *et al.*, 2010b), the quadriceps muscles are aligned along the femoral anatomical axis (Farahmand *et al.*, 1998a). It therefore seems logical that a femoral component should mimic this geometry, particularly when considering that a significant number of patients will have a history of patellar instability with a tendency to track laterally.

2.2.4 Clinical Importance of Quadriceps Weakness following Knee Arthroplasty

Quadriceps strength deficit after TKA surgery, at mid- to long-term follow-up, has been reported to be as high as 30 to 40% in comparison to age-matched groups (Berman *et al.*, 1991; Gore *et al.*, 1986; Silva *et al.*, 2003; Walsh *et al.*, 1998). A reduction in walking and stair climbing speed are considered manifestations of quadriceps weakness (Walsh *et al.*, 1998), although Wilson *et al.* (1996) disputed this association. More recent studies have since been published that further support quadriceps deficiency as the main cause (Mizner *et al.*, 2005; Mizner & Snyder-Mackler, 2005). The literature in this section assesses the impact of quadriceps weakness following TKA.

Berman *et al*. (1991) performed a prospective comparative study on two groups of patients receiving unilateral TKA, Total Condylar Prosthesis II (TCP II) (Zimmer, Warsaw, Indiana) who at the time of the index procedure had unilateral disease. The first group of 68 patients underwent Cybex II isokinetic testing, the second group of 36 patients were evaluated using the Hospital for Special Surgery (HSS) knee rating scale, gait analysis and the Cybex. Both groups were assessed pre- and post-operatively at specific time intervals. The eligibility criteria for both groups were patients with degenerative arthritis of the knee not requiring any walking aids, who did not have other musculoskeletal or systemic pathology impacting gait and were available for follow-up. The Cybex II measured the quadriceps and hamstring torque, peak torque, and

hamstring to quadriceps ratio or flexion to extension (FE) ratio. Measurements were taken at varying flexion intervals using a dynamometer while the patient was seated in a chair. The analysis was also performed on the 'normal' side for each patient for comparison. Group one pre-operative mean peak torque in flexion was approximately a third less than the contralateral 'normal' knees mean value; in extension it was approximately half the 'normal' knees mean. The pre-operative FE ratio, was 0.89 for the implanted knees and 0.55 for the normal knees (normal range (0.50-0.60). Between 7 and 12 months the authors reported a significant improvement in flexion peak torques and FE ratio although they did not provide any statistical data to support this observation. There was minimal change in extension peak torque implying a residual deficit in quadriceps strength. At 24 months the FE ratio normalised. The assessment on group two, at mean follow-up 28 months (24-39 months), showed an increase in walking velocity and decrease in two-foot stance post-operatively. The FE ratio normalised and all post-operative HSS scores were comparatively greater than the pre-operative scores. There was correlation between FE ratio and gait velocities and two-foot stance but not peak torques.

In summary, this study found FE ratio normalisation is associated with improved gait, normal hamstring strength is restored within a year and quadriceps strength remains suboptimal at two years. This study is weakened by the lack of statistical evidence for the differences observed despite the authors inferring that a clinical difference exists. Other

limitations included the 12 knees that required arthroplasty surgery during the evaluation period. It is possible that the 'normal' values produced by these 'normal' knees were lower than that which would be found in an unaffected knee due to the undetected degenerative disease. Furthermore, the strength of the control knees may have been reduced as a direct impact of the limitations imposed by the affected knee. It may have been more plausible to identify a matched group with bilateral normal knees for comparison. It is also not clear who performed the TKAs and whether this was a multi-surgeon or single surgeon series.

Silva *et al*. (2003) performed a prospective comparative study assessing the difference in knee strength between a group of high-level functioning TKAs and a control group. Fifty-two 'normal' knees in 31 patients were in the control group. The eligibility criteria for this group consisted of no pain or other restrictions. The study group consisted of 32 TKAs in 19 patients of which 13 were bilateral. All the knees in this group met the criteria of 'excellent'. All the implants were cemented PS-TKA with polyethylene patellar components. Each knee was evaluated post-operatively using the Knee Society Scoring System (KSS) for clinical function and a dynamometer for measuring FE ratio, peak extension and flexion torques during knee flexion from 0° to 90° at 15° increments. In summary, this study demonstrated peak extension and flexion torques were greater in controls than in TKA at all positions following adjustment for demographic differences (age, height, weight and BMI). KSS positively correlated with peak extension torques (r = 0.57; P = 0.004)

and negatively correlated with FE ratio (r = -0.78; P = <0.0001), suggesting higher quadriceps strength was associated with higher KSS scores. Older patients with TKA produced lower extension peak torques than the younger TKA patients. The authors reported a moderate strength of association between high BMI and quadriceps weakness (r = 0.44; P = 0.007). However, these findings were undermined by the following limitations of the study.

Multiple analyses were performed in this study thus increasing the risk of a Type I error. The authors performed statistical adjustments for age, height and BMI due to the significant difference in these demographics between the control and TKA groups. However this method does not control for multiple confounding variables, which is likely to be the case in this study. Thus the statistically significant differences in peak extension and flexion torques found between the control and TKA groups could be due to these confounding factors. In addition, the control group included patients with only one normal knee, which may have altered the overall functional outcome due to lack of mutual exclusivity. Gender and bilaterality were two other confounding factors that were not adjusted for that may have influenced the observed difference in peak extension torques reported. Subgroup analysis was performed on an already small sample size thus introducing the risk of a Type II error and ultimately diminishing the strength of the evidence. Although the implants are all stated to be PS-TKA, designs can vary significantly in terms of symmetry/asymmetry, depth of trochlear recess and flange dimensions.

All of these geometric variables can influence prosthesis function due to the impact on, for example, the angle of engagement of the cam post mechanism, which ultimately affects the peak torques produced. This may explain the high variability observed.

Walsh *et al.* (1998) performed a retrospective comparative study of 29 patients who had undergone TKA and 40 matched control patients. Eight of the TKA patients were bilateral. The purpose of the study was to determine physical impairments by measuring knee ROM and muscle torque using a dynamometer. Walking and stair climbing were slower, stride length and knee joint excursion were reduced in the TKA patients. The mean peak force on knee extension was greater than knee flexion. The FE ratio was greater for TKA than control patients. The results were consistent with the two previous studies discussed, as were the study limitations.

The mean peak extension and flexion torques in the 'normal knee' of TKA patients, although stronger than the TKA knee, were 27% and 12% lower than the torques measured in the control group, respectively. Furthermore, reduced peak torques were still present at 1 year post-op in both the 'normal' and TKA knees of the TKA group. Thus reaffirming using the contralateral 'normal' knee may not be the most suitable control. Although, the control patients were matched on age and gender, the higher weights and body fat percentages observed in the TKA group are confounding factors. Another limitation is that patient selection consisted of volunteers. Volunteers have been shown to be healthier and

have better function (Sackett, 1979). Such individuals may be more determined to have a successful outcome and therefore the observed difference is significantly influenced by personality trait rather than the independent variable. This would be considered a failure in internal validity. Therefore, both the TKA and control groups may not be representative of their respective populations. The type of prosthesis (CS- or CR- or PS-TKA) was not stated by the authors and therefore the reader cannot draw specific conclusions related to prosthetic design. Despite these limitations the study did show that although pain is reduced following TKA, function is still impaired in terms of ADLs when compared with normal knees. How this is related to quadriceps strength deficit is not sufficiently demonstrated by this study although likely to be a contributing factor.

Huang *et al.* (1996) carried out a retrospective comparative study assessing muscle strength ratios and whether the ratio returned to normal levels in the long term. A single surgeon series of 36 patients underwent 50 TKA, of which 14 patients were bilateral. Nine patients (16 knees) were in the control group. The post-operatively follow-up time ranged from six to thirteen years. Three types of TKA were used: 14 Total Condylar (TC) (Howmedica, Rutherford, New Jersey), 21 Low Contact Stress meniscal bearing (LCSmb) (Depuy, Warsaw, Indiana) and 15 Low Contact Stress rotating platform (LCSrp) (Depuy, Warsaw, Indiana). The TC and LCSrp were CS-TKA designs; LCSmb was CR-TKA. The TKA group FE ratio for all 3 prostheses were higher than for the control group,

significant at $P < 0.05$, suggesting the quadriceps strength was weaker in the TKA group; no difference was seen between CR- and CS-TKA. The authors concluded this difference in FE ratio may be due to disuse atrophy, patient reluctance to exert themselves in order to preserve the prosthetic joint and/or ACL deficiency. Previous studies have shown quadriceps strength reductions associated with ACL deficient knee (Kannus, 1988).

The main limitations with this study were the small sample size and sub group analysis performed which renders the data susceptible to Type II error. In addition, the control and TKA groups were statistically different in terms of body weight and within the TKA group there were significant differences in follow-up time. These known confounding factors along with the unknown confounding factors weaken the quality of the evidence.

Andriacchi *et al.* (1982) evaluated the relationship between gait and TKA design during level walking and stair-climbing. Thirty-six TKAs (26 patients) were assessed and compared to a group of 14 control subjects. The TKA patients were analysed in 5 subgroups based on prosthesis design: 7 Geomedic (CR-TKA), 8 Cloutier (least constrained CR-TKA), 7 Gunston (retention of both ACL and PCL TKA), 8 TC (CS-TKA) and 6 Duopatellar (CR-TKA). The results show walking speed and stride length were greater in the control group than TKA group; no difference between the five groups was observed. The range of motion (ROM) for the TKA group was less than the control group, except for the

Cloutier prosthesis subgroup that had the same ROM as the control group during stair climbing. The authors believed the normal ROM in this subgroup was a result of both cruciate ligaments being retained, the flat minimally constrained tibial component and a more posterior femorotibial contact position, giving the quadriceps a mechanical advantage. They argue that a more constrained component would prevent posterior positioning of the femorotibial component and therefore not produce the same moment arm. These conclusions have not been evaluated in this study.

The study is weakened by the lack of matching and thus an imbalance of known (ipsilateral limb pathology, bilaterality, variations in prosthetic design) and unknown confounding factors between the TKA and control group. In addition, poor choice of primary outcome (ROM) makes the inferences drawn regarding quadriceps function unreliable.

Bolanos *et al.* (1998) performed a retrospective single surgeon comparative study of 14 patients with bilateral TKAs- one CR-TKA and one PS-TKA. Three CR-TKAs were used: 8 anatomic graduated components (Biomet, Warsaw, Indiana), 3 Cruciate Condylar (Howmedica, Rutherford, New Jersey) and 3 Kinematic Condylar (Howmedica, Rutherford, New Jersey). All fourteen PS-TKAs were IB II. The authors carried out isokinetic testing and gait analysis. No difference was found between CR- and PS-TKA in terms of peak torques, endurance, stride time, stance phase and double limb support time, ROM and stair climbing. Statistically significant differences were demonstrated

between the TKAs and controls for the majority of these parameters. The authors concluded there was no functional difference between CR- and PS-TKA, although not conclusive due to the following limitations.

The decision regarding which knee received PS- or CR-TKA was dependent on the severity of the symptoms and radiological findings. This introduces selection bias and implies the groups were not equal in terms of disease characteristics. Other issues, such as difference in muscle strength, are more likely to be present in the knee with more severe arthritic disease and, as stated earlier, the knees are not mutually exclusive. Additionally, the sample size was small and three different types of PS-TKA were used. The effects of a number of unknown and known confounding variables including component designs, persistent abnormal gait patterns prior to surgery are immeasurable due to the study design. All of these limitations weaken the credence of the conclusions drawn from these results.

Wilson *et al*. (1996) carried out a retrospective comparative study to determine the functional outcomes of 16 patients with IB II PS-TKAs and 32 age-matched control subjects (two groups of 16) using the HSS and KSS scores, gait analysis and EMG studies. The mean follow-up was 46 months. No difference in gait analysis, isokinetic tests or stair ascent ROM was seen between the TKA group and control group. Level walking and stair descent ROM was statistically significantly greater in the control group in the absence of decreased muscle strength.

These findings are dissimilar to previous studies that have demonstrated quadriceps weakness and high FE ratios (Berman *et al.*, 1991; Huang *et al.*, 1996; Walsh *et al.*, 1998). The authors believe this may be due to a combination of differences in prosthetic geometry and control groups, poor proprioception and residual gait abnormalities. Although, none of these potential causes were assessed. In addition, other factors such as study design, small sample size, unmatched and two different control groups for gait analysis and muscle testing are likely contributing factors. These limitations would have increased the risk of falsely not detecting muscle strength deficit. The authors concluded PS-TKA provides better function than CS-TKA and is equivalent to CR-TKA. However, there is insufficient evidence to support this statement.

Mizner *et al.* (2005) carried out a prospective experimental study to determine the impact of muscle activation and muscle atrophy in the early loss of quadriceps strength following knee arthroplasty. Twenty patients were assessed 10 days pre-operatively and at mean 27 days following unilateral TKA. The TKAs were performed by a number of surgeons who all used an incision extending into the quadriceps tendon. Muscle contraction force was measured by using a stimulator to assess the need for augmentation to reach maximum recruitment. Muscle cross-sectional area was also calculated using MRI to determine the association between this parameter and strength. The results showed a significant post-operative reduction in quadriceps strength by 62% ($P < 0.001$), muscle activation by 17% ($P = 0.002$) and muscle cross-sectional area by 10% (P

= 0.004) compared with pre-operative values. Positive correlation (r = 0.85; P < 0.001) was observed between loss of quadriceps strength and the combination of voluntary muscle activation failure and atrophy. Multiple regression analysis demonstrated a stronger association between quadriceps strength loss and voluntary muscle activation failure than with reduced quadriceps cross-sectional area. There was weak association between extent of activation failure and pain (r = 0.20; P = 0.05). The authors concluded an exercise programme targeting intense muscle contraction might assist in activation and minimise the effects of quadriceps weakness in the first post-operative month.

This study highlights the relationship between muscle activation failure and quadriceps strength loss in the immediate short term. Whilst this is interesting, no long-term inferences can be drawn from the data. One considerable limitation is the unknown effect of the surgical approach to the proximal quadriceps tendon; this could have greatly influenced the loss of quadriceps strength in the initial post-operative period.

The relationship between quadriceps weakness and function following TKA was assessed by Mizner and Snyder-Mackler (2005). This prospective multi-surgeon study involved 14 patients who underwent TKA (prostheses undisclosed). Each patient was assessed three months following TKA surgery using motion analysis, EMG testing, function- stair climbing and rising from a chair, and pain levels. The contralateral knees were used as the control group. The results showed the quadriceps in the

TKA group were weaker than the control group by 65% (P < 0.001). Quadriceps strength negatively correlated with the time taken to ascend stairs (r = -0.65; P < 0.01) and positively correlated with distance walked in six minutes (r = 0.64; P < 0.01). Despite the significantly lower peak knee flexion angle and knee excursion during weight acceptance in the gait cycle in the TKA group compared with the control group (P = 0.02 and P < 0.01, respectively), no difference was found in peak knee extensor moment between the two groups (P = 0.43). The authors believe the patients showed high reliance on the control limb based on the lower peak torques and quadriceps muscle recruitment during sit-to-stand motion. They suggest this may have contributed to the persistent quadriceps weakness in the TKA limb.

This study showed correlation between quadriceps strength and function in the short term. However, the causal relationship between these two variables was not sufficiently demonstrated due to the confounding factors. Other limitations include the use of the contralateral limb as the control group, small sample size and short follow-up.

2.2.4.1 Section Summary

This section consists of two prospective comparative studies, five retrospective comparative studies and two prospective non-comparative studies. Eight out of the nine studies assessed found evidence of quadriceps strength deficit. Overall, the evidence supports the argument that quadriceps weakness is a serious problem following TKA in the

short- and long-term despite the limitations of the studies appraised. The impact of this deficit however may be dependent on the prosthesis geometry.

2.2.5 Impact of Prosthesis Design: cruciate –retaining, sacrificing and substituting on extensor mechanism function

Early prosthesis designs were simple hinge devices, which had a high rate of loosening because they did not allow normal translation and rotation (about all three axes) of the knee to occur. Later, more complex design technology led to the production of condylar prostheses (cruciate-sacrificing TKA, CR-TKA and PS-TKA). These implants have varying degrees of constraint, with the least constraining being CR-TKA and PS-TKA. These prostheses attempt to re-create near anatomical knee kinematics. Unfortunately, not all implants have been successful in replicating physiological motion or extensor mechanism function.

Anterior displacement of the femur on the tibia during flexion has been observed following CR-TKA (Dennis *et al.*, 1996; Kim *et al.*, 1997; Stiehl *et al.*, 1995). In contrast, PS-TKA has been shown to have a more posterior tibiofemoral contact point (Dennis *et al.*, 1996; Dennis *et al.*, 1998).

In theory, a more posterior contact point between the femoral and tibial components will result in a longer extensor moment arm. The longer the extensor moment arm, the lower the quadriceps force required to produce equivalent extensor moments occurring in the presence of a

relatively anterior contact area or shorter extensor moment arm (Insall *et al.*, 1982). The following studies assess the impact of these prosthetic designs on quadriceps strength and knee kinematics, particularly femoral rollback.

Dorr *et al.* (1988) performed a single surgeon series comparative study assessing function using gait analysis and EMG testing following CS-TKA (TC prosthesis) and CR-TKA (Duopatellar or Robert Brigham; Johnson & Johnson, Braintree, Massachusetts) on a group of 11 patients. Each patient received bilateral TKAs: one CS-TKA and one CR-TKA. Evaluations were carried out at 6 months and 2 years. The purpose of this study was to identify whether sacrifice of the PCL affected function in terms of gait, muscle activity and functional scores. The results showed reduced single limb stance time; both CS-TKA and CR-TKA groups had means of 34% (normal is 40% of gait cycle). CR-TKA group had lower post-operative knee ROM than CS-TKA; statistical significance was not reported. The CS-TKA group had statistically higher flexion moments throughout loading and higher varus moments compared with CR-TKA. The authors believed the latter finding was due to the PCL centralising the moment about the knee in the CR-TKA and therefore producing lower varus moments. The EMG studies revealed significantly more active vastus lateralis (VL) and long head of biceps femoris during level walking as a consequence of the larger varus moment arm in the CS-TKA group. During stair climbing the same increase in muscle activity was seen along

with the additional use of forward trunk lean for stair ascent in order to compensate for the varus moment arm and because the quadriceps were already working at maximum capacity. The HSS scores for both groups improved post-operatively and no difference was found. The authors stated that CS-TKA performed less efficiently during level walking and stair climbing. They suggested the higher varus moment associated with the CS-TKA could increase wear due to increased tension in the lateral compartment and increased medial compression. This theoretical argument is based on the occurrence of medial tibiofemoral joint arthritis in PCL deficient knees as a result of increased compression in the medial compartment. The authors concluded CR-TKA was more efficient than CS-TKA, as it required less muscle activity and may have better survivorship as a result of lower medial tibiofemoral joint loading and joint reaction forces.

The main limitation of this study was the sample size. Such small numbers increase the chances of a type II error. The larger varus moments observed in the CS-TKA group could have been related to component positioning rather than an absent PCL, which brings this association into question. Treating each knee as an individual subject in patients with bilateral TKAs assumed statistical independence, which may have led to false interpretations. Cruciate sacrificing prostheses are no longer in widespread use due to suboptimal outcomes; more recent comparisons have been between posterior cruciate stabilising/substituting (PS) and CR.

Another prospective comparative study (Becker *et al.*, 1991) assessed 30 patients, each with one CR-TKA and PS-TKA. The CR-TKA prostheses used were 11 TC, 18 anatomic graduate components –AGC (Biomet, Warsaw, Indiana) and one Kinematic (Howmedica, International Ltd). All the PS-TKAs were IB II. The aim of the study was to determine the difference in functional outcome using the HSS score, ROM, stair-climbing and knee preference. The data were collected at two to five years follow-up. No difference was found between the pre- and post-operative results of the CR-TKAs and PS-TKAs for HSS scores, ROM, stair-climbing ability or knee preference. Again, factors such as sample size, bilaterality, within group prosthesis variation (for CR-TKAs), unvalidated assessment tools and selection bias all weaken the strength and generalisability of the evidence. It is unlikely that such a study design would detect a difference even if one did exist because of these limitations. Conclusions of 'no difference', based on the fact the patients did not favour one design over the other is misleading.

Conversely, a larger study performed by Hirsch *et al.* (1994) did find a functional difference between PS-TKA and both CR-TKA and CS-TKA. The retrospective comparative study involved three groups of patients: Group I (CS-TKA)- 77 PFCs in 70 patients, Group II (CR-TKA)- 80 PFCs in 70 patients and Group III (PS-TKA)- 85 IB II in 81 patients. The surgery was carried out by or under one senior surgeon. All the patients received the same post-op rehabilitation. Assessments were performed pre-operatively, at six months and at one year using KSS

score and ROM. Nine knee (eight patients) were excluded from follow-up; reasons were stated. The results showed Group III (PS-TKA) had a greater ROM than CS-TKA and CR-TKA. No difference was found between the clinical scores. Complications reported included seven patellar fractures and two infections, which were equally spread between the groups. The authors concluded that the greater ROM detected with the PS-TKAs would increase mobility and ability to carry out ADLs which required higher degrees of flexion. No difference was found between CS-TKAs and CR-TKAs possibly due to PCL insufficiency despite being retained.

This study had larger sized groups than previous studies. Although not statistically demonstrated, the authors showed the patient demographics were similar between the groups except for underlying condition. Group I had a lower number of patients with osteoarthritis and a higher number of patients with rheumatoid arthritis likely to have been statistically significant. One of the data collectors was the senior author, which introduces observer bias. There was no attempt to improve the quality of the ROM parameter by blinding or calculating the intra-class correlation coefficient (ICC) for intra-observer or inter-observer reliability.

Stiehl *et al.* (1995) investigated the femorotibial contact point in 47 CR-TKAs compared with 4 control knees using fluoroscopic video analysis. The CR-TKA patients were selected based on high KSS scoring. Five different prostheses were used: 8 Porous Coated Anatomic (Howmedica, Rutherford, New Jersey), 11 Ortholoc (Wright Medical

Technology, Arlington, Tennessee), 9 Genesis (Richards Inc., Memphis, Tennessee), 10 Anatomic Modular Knee (Depuy, Warsaw, Indiana) and 9 Miller-Galante II (Zimmer, Warsaw, Indiana). The results for the control data showed in full extension, the tibia contacted the femur anterior to the midline in the sagittal plane of the tibial joint surface. The converse was true for the 47 CR-TKAs, which demonstrated contact posterior to the mid-sagittal line. Posterior femoral rollback was not visualised with the CR-TKAs, instead anterior translation associated with erratic motion occurred with increasing flexion. Dissimilarly, the control knees exhibited smooth posterior translation during flexion. Assessment of the patellar tendon and patella rotation demonstrated constraint motion with smooth patellar tracking in the control knees. Conversely, the CR-TKA exhibited abnormal patellar tracking with high variability. No statistical analyses were performed. In conclusion, this study demonstrated the CR-TKAs did not perform femoral rollback and the normal pattern of patellar constraint is not reproduced with the patellar resurfacing designs of these prostheses. This investigation clearly demonstrates the abnormal motion occurring with the CR-TKAs. However, the comparator control group is not sufficient in terms of size and matching. Also, the study group consisted of 5 different prostheses, which may have contributed to the significant variability in the results. These limitations undermine the conclusions drawn.

Dennis *et al.* (1996) investigated knee kinematics using an *in vivo* weight-bearing method. Four groups were analysed: 16 normal knees, 10

ACL deficient knees, 13 CR-TKAs and 25 PS-TKAs. Both TKAs were PFC prosthesis. Each knee performed three successive deep squats to maximum flexion under fluoroscopic surveillance in the sagittal plane. The femorotibial contact position was determined using three-dimensional analysis and two-dimensional digitisation. The results for the normal knee demonstrated an anterior femorotibial contact position in the mid-sagittal plane in full extension and during femoral rollback the contact point moved posteriorly. The ACL deficient knees and CR-TKAs exhibited similar patterns of motion. Both types displayed a high degree of variability. Three patterns of movement were seen: (1) paradoxical anterior translation during mid-flexion, (2) persistent posterior position throughout flexion and (3) an amalgam of patterns (1) and (2). Generally, anterior translation occurred at 30° to 60° and 60° to 90°. The PS-TKAs most closely reproduced normal knee kinematics. In full extension the femorotibial contact position was anterior to the mid-sagittal plane but not as far forward as the normal knee. Posterior femoral rollback occurred during flexion, similar to the normal knee but not to the same extent. The authors demonstrated graphically the highly inconsistent femorotibial position associated with CR-TKA and ACL-deficient knees compared with PS-TKA and normal knees. The authors concluded normal posterior femoral rollback is not reproduced by either CR- or PS-TKA despite the latter more closely replicating normal knee kinematics. They also suggested the posterior translation that occurred in full extension for both the ACL deficient knees and CR-TKA was as a result of an absent ACL

and anterior translation was due to insufficient PCL (poor tension). The high variability in femorotibial contact position was attributed to surgical technique and the anterior translation observed linked to early polyethylene failure in the CR-TKA designs with flat, non-conforming femoral surfaces.

Anteriorisation of the femur on the tibia during flexion in an ACL deficient knee or CR-TKA has been demonstrated in this study and others (Draganich *et al.*, 1987; Stiehl *et al.*, 1995). Anteriorisation of the femorotibial contact point is thought to inhibit maximum flexion due to the relatively anterior flexion axis, cause early soft tissue impingement of the posterior structures and tighten the extensor mechanism. The quality of this study could have been improved if the sample sizes and group characteristics/demographics were matched. The results represent PFC prosthesis in patients with high functional outcome; the narrow inclusion reduces the external validity and generalisability of the findings.

A later study (Kim *et al.*, 1997) was conducted to further analyse *in vivo* posterior femoral rollback following CR-TKA using lateral radiographs. The investigation involved 49 CR-TKAs (Genesis Total Knee System, Smith & Nephew Orthopaedics Memphis, Tennessee) in 38 patients (11 bilateral, 27 unilateral). Four surgeons performed the procedures, each surgeon ensuring that the PCL was intact at the end of each procedure. The patients were selected consecutively providing they had a good to excellent KSS score, ≥ 90° of flexion and appropriate radiographs and follow-up was performed at one year. Three radiographs

were observed: 1) lateral (hip to ankle) standing in full extension- to measure femorotibial contact position 2) anteroposterior (hip to ankle) standing in full flexion- to measure tibiofemoral varus/valgus angle 3) unloaded knee at 90° in the seated position- to measure femorotibial contact position. The distance between the two femorotibial contact positions was measured relative to the distance from the anterior aspect of the tibial tray and second reference, the anterior rim of the tibial plateau. The results showed no evidence of posterior femoral rollback, rather anterior translation was observed. There was no correlation between posterior tibial slope and amount of femoral translation on the tibia. The authors concluded posterior femoral rollback does not consistently occur in CR-TKA and no correlations were identified between posterior tibial slope, tibiofemoral angle (pre- or post-operative) and amount of femorotibial contact position shift.

There were a number of limitations such as the absence of a comparator group and inappropriate statistical methodology. The authors used paired *t*-test to calculate intra-interobserver reliability instead of calculating the intraclass correlation coefficient. The paired *t*-test value gives no indication of the level of reproducibility achieved by the observers. Contrary to the findings of Walker and Garg (1991), the authors concluded posterior tibial slope does not effect femoral translation. This study may have failed to detect such an association because the measurements taken were carried out on a small number of patients at only 2 points in knee motion. Furthermore the analysis method

used was inadequate. Measuring femorotibial contact position on a lateral radiographs may result in a high error rate due to the superimposed femoral condyles. The variability in the results may also reflect surgeon inconsistency/experience despite all four using the same technique.

Insall *et al.* (1982) performed a retrospective comparative study to determine whether the theoretical design advantages of PS-TKA resulted in improved knee function. The authors assessed function using the HSS score, ADLs and ROM. Radiographic parameters such as, radiolucency and component positioning were also measured. The two prostheses compared were: 1) 64 TC TKAs (CR-TKA) and 2) 66 IB TKAs (PS-TKA); both procedures were performed or supervised by the senior author. The results showed a post-operative improvement in HSS score compared with pre-operative values; no difference was seen between the CR-TKA and PS-TKA scores. The post-operative ROM was greater in the PS-TKA group compared with the CR-TKA group, significant at $P < 0.05$, as similarly demonstrated by Hirsch *et al.* (1994). In the PS-TKA group 76% were able to walk for unlimited distances and climb stairs without the aid of the bannisters compared with 22% in the CR-TKA. Component malpositioning rates and radiolucency were not found to be different between the groups, although this finding was not supported by statistical evidence. Although a higher number of patellar fractures occurred in the PS-TKA group due to suspected overstuffing, the authors concluded the IB PS-TKA offers good function without compromise to fixation. They attributed this more superior outcome to a longer extensor moment arm

due to the more posterior tibiofemoral contact position. In this position lower quadriceps force is required to produce equivalent extensor moments occurring in the presence of a relatively anterior contact position or shorter extensor moment arm thought to be associated with CR-TKA.

The main strength of this study was the use of a comparator group, which allowed for direct referencing of prosthesis performance. The authors attempted to demonstrate similarities in patient demographics but failed to support this observation with statistical evidence. The study reported significant differences in the ability of the groups to achieve stair-climbing unaided and unlimited walking but did not provide any indications of the pre-operative ability of each group. Additionally, the authors concluded the observed differences in function are as a result of the effects of prosthetic design on extensor mechanism performance. Although this might be true, the chosen outcome measures coupled with insufficient exclusion of other plausible causative factors undermines this conclusion.

2.2.5.1 Section Summary

The evidence in this section consists of one prospective comparative study, three retrospective comparative clinical studies, two retrospective comparative radiological studies and one retrospective non-comparative radiological study. The prospective study did not find a functional difference between CR-TKA and PS-TKA. Two out of three of

the retrospective comparative clinical studies found no difference in validated functional scores between CR-TKA and PS-TKA. However, both reported PS-TKA had significantly greater ROM than CR-TKA. The results of the radiological studies were in general agreement, concluding CR-TKA showed high variability in motion abnormal to the anatomic motion of the knee and no evidence of femoral rollback. However, there was no evidence of PS-TKA exhibiting normal femoral rollback. The majority of these studies had multiple limitations such as the use of unvalidated outcomes, lack of matching between comparator groups, confounding factors and small sample sizes. Based on the findings and limitations of these studies no robust evidence was found to suggest CR-TKA is less favourable than PS-TKA.

2.2.6 Impact of Femoral Component Design: multi-radius versus single radius on extensor mechanism function

The dispute between multi-radius (MR) and single radius (SR) femoral component designs still exists and is based on theoretical interpretation of knee motion axes. Traditional kinematics theory of Reuleaux (1875), cited by Mahoney *et al.* (2002), stated that knee flexion and extension occurred around changing centres of rotation with the axis of rotation relatively anterior and proximal in extension, shifting distal and posterior into the femoral condyles with flexion. This kinematic theory has been incorporated in the MR femoral component designs. However, studies

have shown TKAs with a MR sagittal profile do not re-create normal extensor moment arms, especially in the final 30° of extension (Huang *et al.*, 1996; Lewandowski *et al.*, 1997; Singh & Schmalzried, 1996). Furthermore, anatomic studies have disputed the existence of two simultaneous rotations occurring about fixed axes (Panjabi *et al.*, 1982). Panjabi *et al.* (1982) performed an anatomic study demonstrating, through the use of mathematical models, the unlikely existence of two simultaneous rotations occurring about a fixed axes. In summary, the authors showed that other theoretical estimations (upon which the MR designs are based) are open to a wide margin of error. These findings were further supported in a later study (Hollister *et al.*, 1993) that suggested knee motion occurs about a single fixed axis of rotation located in the posterior femoral condyles. This study established the two knee axes: flexion-extension axis and longitudinal rotational axis were not in the coronal and sagittal planes, respectively. The authors found the motion about each axis was a combination of flexion-extension, varus/valgus and internal/external rotation. This theory supported the 'screw-home mechanism', that is, a combination of external rotation of the tibia with extension, as a result of the deviation from the standard plane of the flexion-extension axis and rotation about the longitudinal rotational axis. The arguments of this study are compelling although limited by the small number of specimens assessed and MRI analysis used to ascertain knee motion. No reference was given to the thickness of the MRI slices and therefore the degree of assumption made between data points is

unknown. Furthermore, because this was a non-comparative study, no suggestion was made regarding the potential biomechanical impact of interpreting knee motion using simultaneous axes theory. Later, Churchill *et al.* (1998) showed the location of this flexion-extension axis could be accurately estimated using the transepicondylar axis. A more posteriorly located axis would theoretically lengthen the extensor moment arm and improve extensor mechanism efficiency. Single radius TKA designs are based on this rationale. The following studies compare both SR and MR femoral component designs in relation to extensor mechanism function.

Hall *et al.* (2008) designed a prospective, randomised comparative study to assess whether knee ROM and function are obtained earlier with a single radius (SR) femoral component compared with a multi-radius (MR) femoral component of a CR-TKA. The two prostheses were: (1) single sagittal radius- Scorpio (Howmedica, Stryker Orthopaedics, Mahwah, New Jersey) and (2) multi-radius – Press Fit Condylar Sigma-PFC (Johnson & Johnson PFC; Depuy, Johnson & Johnson, Warsaw, Indiana). Each arm consisted of 50 patients who met the inclusion criteria and were selected at random to receive either Scorpio or PFC. Both groups received the same peri- and post-operative management; two surgeons carried out the procedures. The following outcomes were assessed pre-operatively, at four to six weeks, three months and one year: active ROM, KSS score, rising from a chair (assisted/unassisted) and anterior knee pain. The results showed no difference between

demographics, functional score or percentage of patients able to rise from a chair unassisted. Extension improved in both groups significantly at four to six weeks and one year although no clinical significant difference was found. The authors did not identify a relationship between femoral component condylar radius and extensor mechanism function based on ability to rise independently from a chair. They also concluded extensor mechanism function following either single radius or multi-radius femoral components is comparable in modern CR-TKA designs.

This is the only randomised study observed in this literature review. It met some of the CONSORT reporting requirements: adequate abstract content, sufficient background information and study rationale, study design description, explicit eligibility criteria, clear description of interventions including similarities, statistical methods explained, participant flow described and the interpretation was consistent with the results.

The most significant concern with this study is the main conclusion is based on an outcome measure (ability to rise from a chair unassisted) that is not solely reliant on quadriceps function; other biomechanical mechanisms may influence this outcome. The use of unvalidated test methods weakens the strength of the inferences drawn due to the unknown sensitivity and specificity of the test method for that particular application. Another limitation, is the geometry of the prostheses differed on more than just the number of radii on the femoral component design. The surface geometry of the polyethylene inserts were different; the

Scorpio had a deeper sagittal curvature and a single coronal radius across both compartments. Additionally, the slope of the tibial component was neutral (0°) on the Scorpio whereas on the PFC it was 5°, although the Scorpio polyethylene insert had a built in 4° slope. These geometrical differences are confounding factors that were not taken into consideration during the design of the study. It is not clear whether an equal number of the two types of TKA were performed by each surgeon. This is another potential confounding factor if there is a discrepancy in numbers performed and surgeon ability.

Mahoney *et al*. (2002) believed the more anterior flexion-extension axis of the MR TKAs may cause shorter extensor moment arms and thus, a relatively posterior axis would lengthen the moment arm and enhance the extensor mechanism performance. Therefore, the aim of this retrospective comparative, consecutive series was to compare one MR PS-TKA with an SR PS-TKA. Two groups of 100 knees: the most recent 100 knees that received the 7000 PPSK (Osteonics, Allendale, New Jersey) (MR PS-TKA) and the first 100 knees that received the Scorpio (Osteonics, Allendale, New Jersey) (SR PS-TKA) were selected. Both knee replacement systems used the same tibial component, which had a cam-post mechanism that engaged between 60° to 70° of knee flexion. No statistical difference between group demographics was observed. Functional evaluation was carried out at pre-operatively, six weeks, three months, six months, one year and two years using KSS. Extensor mechanism assessment was performing by asking patients to rise from a

chair 16 inches above ground level without using arm support. Three questions were asked during this task:

1. Could they rise without using their arms?
2. Any anterior knee pain while rising?
3. Any painful crepitus? (indicating soft tissue impingement)

No difference in pre- and post-operative KSS scores was observed between the two groups. The difference in ROM was only significant at six weeks, with the SR group achieving greater ROM by this time point. After this time point there was no difference. More patients in the SR group were able to independently rise compared with the MR group at six weeks, one year and two years. Fewer patients complained of anterior knee pain during the chair rising task in the SR group. The authors found the ability to chair rise independently was associated with lower rates of anterior knee pain. They attributed this difference as well as the reduction in painful crepitus, to lower compressive force between the patellar button and femoral component as a result of the longer recessed trochlear groove. The study inferred SR design improves extensor mechanism function.

The concept of this study was current and useful. The authors used one validated outcome measure (KSS) and explicitly stated the methodology. However, other aspects of the study undermined the results and subsequent conclusions drawn.

Although the authors demonstrated the groups were similar, in terms of age, gender and BMI, there were distinct differences in time of

selection (first 100 knees for SR group compared with last 100 knees for MR group) and number of bilateral cases (25 patients in the SR group and nine patients in the MR group). Both factors could be confounding. The authors claimed the chair rise test is a more focused assessment of extensor mechanism function, however a number of other factors influence the outcome of this test such as height, bilaterality, coexisting co-morbidities and core strength. The authors believed that the observed differences between the groups are unlikely to be secondary to other factors due to the relatively large sample sizes of the groups and the fact the study was a single surgeon series. Whilst these factors strengthen the study, the patients were not randomized and therefore unknown variables were not balanced between the groups. Besides variation in radii the femoral components had other external geometric differences. The Scorpio had a recessed and longer trochlea that extended further distally and a polyethylene insert with a higher degree of conformity in the anteroposterior plane. These additional variables undermine weaken the actuality confidence of the associations detected. The evaluations were all carried out by the operating surgeon who was not blinded, which therefore introducing observer bias. All these limitations reduced the reliability of the evidence and weakened the concluding opinion that SR design features improve extensor mechanism function. The variation in trochlear design may have more influence than a difference in radius of curvature.

A similar retrospective comparative study (Gomez-Barrena *et al.*, 2010) assessed the difference in functional outcome (AKSS), muscular performance and gait cycle between SR (Scorpio, Stryker Orthopaedics, Mahwah, New Jersey) and MR (NexGen, Zimmer, Inc. Warsaw, Indiana) PS-TKAs. Thirty patients in each group were evaluated. None of the patients were bilateral or had a symptomatic contralateral limb. Each patient was able to flex beyond 90° and walk unaided. The demographics and clinical factors of each group were compared and deemed not significantly different. The results showed AKSS function score was greater for the SR compared with MR group; no difference was found between the groups for the AKSS clinical score. The SR group required less physiotherapy and were using only one crutch sooner than the MR group. Isokinetic testing revealed no difference in peak angles in extension, although in flexion peak angles and peak torques were higher in the MR group than the SR. Conversely, peak torque in extension was higher and the hamstring: quadriceps ratio was lower in the SR group compared with the MR group. The authors concluded SR femoral components provide better functional performance in the short-term.

The study limitations included non-randomisation of patients, short-term follow-up, additional geometric variables between the prosthesis and variability in patellar resurfacing. All of these additional confounding factors mean it is difficult to conclude with confidence that the observed differences are a result of femoral component design. It is possible that any one of these potential confounding factors is causative.

D'Lima *et al.* (2001) performed a cadaveric study involving six knees to determine the effects of changing centre of rotation of the knee on quadriceps tension. Three conditions were assessed: 1. Normal knee, 2. Scorpio (SR CR-TKA) and 3. Series 7000 (Howmedica, Osteonics, Allendale, New Jersey) (MR CR-TKA). Each knee was subject to testing under all three conditions in an Oxford knee rig using an EMG tracking system and load cell to measure quadriceps tension. Physiological loads were used to replicate peak knee flexion moments occurring during stair climbing after TKA. The patellofemoral forces were also measured using a load cell device, which detected compressive, medial and lateral shear forces during knee extension. Each knee was digitised before testing to create set coordinate systems within the femur and tibia. The femoral coordination system centre was the mid point of the transepicondylar axis and the tibial coordination system centre was the midpoint of the tibial plateau. Along with variation in radii of the femoral component, the Scorpio had a deeper trochlear groove and different polyethylene insert. Femoral rollback, tibiofemoral rotation, varus and valgus angulation and quadriceps tension were analysed for differences between the three conditions. No significant differences in knee kinematics (femoral rollback, tibiofemoral rotation and varus/valgus angulation) were detected between the two CR-TKAs. Both implants demonstrated a 6mm to 7mm posterior tibiofemoral position relative to that found in the normal knee at 0° and showed negative rollback (rollforward) of 4mm±12mm from 0° to 90° knee flexion, which was approximately 10mm anterior to that found in

the normal knee. The normal knees created higher quadriceps tension than the knee arthroplasty conditions. At flexion angles greater than 50° the Scorpio (SR group), consistently generated statistically lower quadriceps tension ($P < 0.05$) compared with Series 7000 (MR group). The authors concluded this reduced quadriceps tensile force may assist in performing ADLs and thus shorten rehabilitation following TKA. However, they acknowledged that changes in the centre of rotation do not benefit or disadvantage knee kinematics given no difference in knee kinematics was demonstrated between the SR and MR CR-TKA.

Failure to control for the other geometric variables, along with the multiple tests performed, rendered the results susceptible to a Type I error. It may have been more appropriate to adjust the alpha for the number of variables tested. In addition, the other differences in geometry of the tested prostheses are likely to have influenced the outcome. A larger sample size with a greater number of trials per condition using geometrically better matched prosthesis would have provided more conclusive results.

2.2.6.1 Section Summary

Three out of four of the studies concluded SR femoral components improved extensor mechanism function compared to MR designs. However, the randomised study, arguably the most reliable, did not find a difference. Neither type (SR or MR), irrespective of cruciate retaining or posterior substituting demonstrated normal knee kinematics. Overall, the

strength of the evidence was compromised by confounding factors such as additional geometrical differences between the femoral components and polyethylene insert articular surfaces, use of unvalidated outcomes, lack of matching between groups and observer bias. Therefore firm conclusions cannot be drawn from any of the studies. No literature was identified that assessed the difference in extensor mechanism function between single or multi- radius CR- and PS-TKA.

2.2.7 Theoretical Extensor Mechanism Efficiency following Patellofemoral Arthroplasty

As highlighted above, there are a number of studies assessing extensor mechanism function following TKA but there are no reports in the literature on the effects following PFA. In theory, the knee kinematic following PFA should resemble normal knee kinematics more closely than that existing after TKA, because of the preservation of the cruciate mechanism.

In the native knee, both the anterior cruciate ligament and posterior cruciate ligament control femoral rollback. This allows for high flexion and avoids posterior bony impingement. This element of knee kinematics should not alter following PFA since the tibiofemoral joint and cruciate ligaments remain intact. Some modern TKAs, in an attempt to re-create maximal flexion while providing a more congruous (dished) design, have a more posterior tibiofemoral contact point and steeper posterior slope. It is possible that this contact point is more posterior than that

existing in the native knee although this more posterior contact point has yet to be satisfactorily demonstrated.

If a more posterior tibiofemoral contact point is achieved, one could postulate that TKA could potentially offer a more efficient extensor mechanism compared with PFA. Other factors need to be taken into consideration such as the geometry of the anterior flange, asymmetry of femoral condyles and depth of trochlear recess. Depending on surgeon technique, the design of the PFA: onlay versus inlay will also make a difference to the patellar offset and hence extensor mechanism efficiency.

2.2.8 Conclusion

The purpose of this literature review was to establish the evidence for extensor mechanism function following PFA and TKA in terms of quadriceps weakness and the impact of prosthetic design. No reports on quadriceps weakness following PFA were identified. The evidence provided convincing support for the belief that quadriceps weakness is an important problem following TKA surgery irrespective of implant design. In contrast, the evidence for PS-TKA and single radius femoral components offering better extensor mechanism function was weak and inconclusive.

Retrospective study designs, small sample sizes, poorly matched comparator groups and inappropriate statistical analyses were common weaknesses. The commonest limitation involved the sampling method, which was subject to selection bias due to the majority of patients being

surgeon selected. Invariably, sampling error, due to the lack of randomisation, and systematic error, in the case of self-selected volunteers, also contributed to the limitations and thus narrowed the generalisability of the inferences. Failure to control or adjust for known confounding variables, such as other geometrical differences or inconsistencies between comparator groups, may have led to false conclusions.

Identifying which arthroplasty treatment maximises extensor mechanism function would further inform the debate regarding prosthesis choice. The main deficit in this review is the lack of literature on the impact of PFA on extensor mechanism function and how this compares with extensor mechanism function following CR-TKA and PS-TKA. This shortfall in the literature led to the development of the following cadaveric biomechanical study.

2.3 Funding

BOA Joint Action Research 2011

Grant Reference: GA1189

Amount: £8900

2.4 Study Design

Biomechanical cadaveric knee, lab based, comparative study.

2.5 Good Clinical Practice & Research Ethics Committee Approval

The conduct of this study is in agreement with Good Clinical Practice guidelines. The National Research Ethics Service Committee West Midlands – Staffordshire reviewed handling and transfer of the specimens and other ethics related aspects of the study. On 23th September 2011 the study was granted a favourable ethical opinion by the committee. The Research Ethics Committee reference is 11/WM/0253.

2.6 Background

2.6.1 Rationale for Study

The literature review for this study identified there were no current studies comparing extensor mechanism function following patellofemoral arthroplasty and total knee arthroplasty. Investigating this subject further informs the debate regarding the use of these arthroplasty treatments for isolated patellofemoral arthritis. With this principal outcome in mind, the results of this study provide the benchmark data and methodology upon

which other more sophisticated translational research can be developed, whilst still providing valuable information for clinicians and engineers.

This study focused on testing hypotheses on extensor mechanism efficiency, patellofemoral resultant force, peak pressure and contact area. The kinematics of the patellofemoral and tibiofemoral joints are altered following arthroplasty surgery. As discussed in the literature review, the degree of femoral rollback (or the lack of) has been a central point of focus when determining which type of prosthesis, CR-TKA or PS-TKA, more closely resembles the anatomical knee. Patellofemoral kinematics vary due to differences in the points of contact, timing of engagement of the patella in the trochlear groove and bearing surface forces generated within the joint.

Figure 2-4 illustrates the quadriceps force, represented by the line F_Q and the patella tendon force, represented by the line F_P. Each force is a vector quantity (magnitude and direction). The forces are not equal; the patella does not act as a simple pulley system. Change to F_P is a factor of F_Q, which varies according to the angle of knee flexion. The resultant force (R) is the combined force of the quadriceps muscle and the patellar tendon. The more flexed the knee the greater will be the resultant patellofemoral joint force for the same quadriceps muscle force. In theory, extensor mechanism efficiency should be high when the patellofemoral joint resultant force is low because extensor moment efficiency is directly proportional to the extensor moment arm; when the extensor moment arm is long the resultant force is reduced. Patellofemoral joint resultant

force decreases as the knee extends, that is, as the angle at the knee becomes less acute the quadriceps lever arm increases. This is illustrated in Figure 2-4 to Figure 2-6.

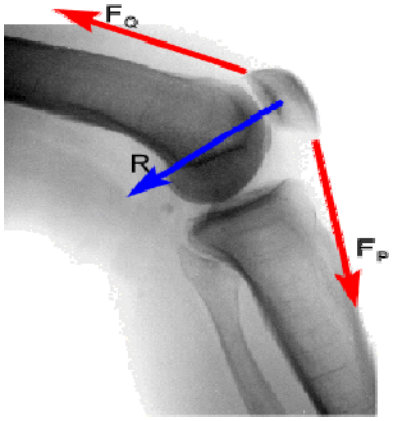


Figure 2-4 Quadriceps and patellar tendon force and angle of resultant force

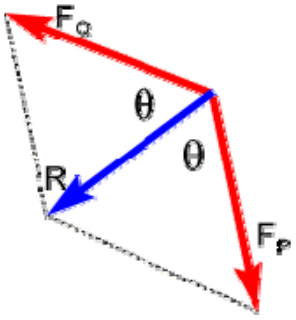


Figure 2-5 Low resultant force at low knee flexion angle

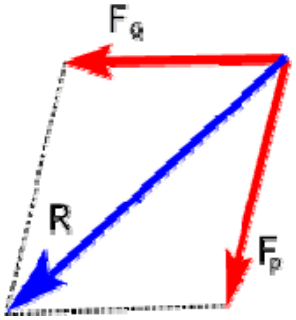


Figure 2-6 High resultant force at increased knee flexion angle

Based on this theory and the literature reviewed, the following research questions and hypotheses were generated.

2.7 Research Questions

1. At a constant quadriceps tension, is the extensor moment efficiency greater following TKA compared with PFA during the range of knee flexion 0° to 120°?
2. If so, does this result in a difference in patellofemoral joint reaction forces following TKA compared with PFA during the range of knee flexion 0° to 120°?
3. What is the effect on peak pressure and contact area following TKA compared with PFA during the range of knee flexion 0° to 120°?

2.8 Hypotheses

1. The extensor mechanism efficiency will be greater following PFA compared with TKA throughout the range of flexion-extension cycle 120° to 0°. The extensor moment produced at a given quadriceps tension would be greater following PFA compared with TKA due to the more posterior tibiofemoral contact point associated with the native tibiofemoral joint resulting in a relatively longer extensor moment arm and therefore lower quadriceps force requirements and lower patellofemoral joint reaction forces.

2. There will be no difference between the extensor moment efficiency for CR-TKA compared with PS-TKA. The effect of the intact PCL in the CR-TKA compared with the cam-post mechanism will not result in a significantly shorter extensor moment arm. Both prostheses will give rise to higher patellofemoral resultant forces than PFA or native knee.
3. Peak pressures will be greater for CR-TKA and PS-TKA compared with PFA and native knee throughout the range of knee flexion due to the bearing surfaces and surface contact area. The native knee will generate the lowest peak pressures.
4. The contact area will be greater for PFA compared with CR-TKA and PS-TKA at higher levels of knee flexion when the patellar button begins to articulate with the native femoral condyle. There will be no difference between CR-TKA and PS-TKA. The native knee will produce the highest contact area throughout the entire range of knee flexion.

2.9 Null Hypothesis

1. There is no difference in the extensor moment produced at a given quadriceps tension during knee flexion to extension following CR-TKA, PS-TKA and PFA.
2. Therefore, there is no difference in patellofemoral joint reaction forces following CR-TKA, PS-TKA compared with patellofemoral arthroplasty.

2.10 Aim and Objectives

Aim

To determine whether the biomechanical and geometrical differences between CR-TKA, PS-TKA and PFA result in dissimilar extensor mechanism efficiencies.

Objectives

The objectives of this study were to measure four parameters under four conditions:

1. Normal/native knee
2. Patellofemoral arthroplasty: Zimmer® Gender Solutions™ Patello-Femoral Joint System (Zimmer, Warsaw, Indiana, USA).
3. Cruciate retaining total knee arthroplasty (CR-TKA): Zimmer® NexGen CR-Flex System (Zimmer, Warsaw, Indiana, USA).
4. Posterior-stabilising total knee arthroplasty (PS-TKA): Zimmer® NexGen LPS-Flex System (Zimmer, Warsaw, Indiana, USA).

Parameters:

1. Extensor moment efficiency
2. Patellofemoral joint reaction (compression) forces
3. Peak pressure
4. Contact area

2.11 Study Method Summary

This study was performed in the Biomechanical Engineering Department at Imperial College London under the supervision of Professor Andrew Amis. A total of ten cadaveric knees were required, of which two knees were used to formulate and refine the methodology. The remaining eight cadaveric knees were used to carry out the biomechanical assessments. Four conditions were tested sequentially on each knee: normal, patellofemoral arthroplasty, cruciate-retaining total knee arthroplasty (CR-TKA) and posterior-stabilising total knee arthroplasty (PS-TKA). All three prostheses were Zimmer Systems with comparable geometry.

The cadaveric knees were acquired from University Hospitals Coventry and Warwickshire NHS Trust. All the knees were healthy and 'non-arthritic' (no macroscopic arthritis) with normal alignment. The storage and handling of these knees followed the Imperial College London tissue handling guideline rules.

For the purpose of this *in vitro* study a transpatellar approach was used for each knee. This approach involved splitting the patella off-centre in a longitudinal fashion; this split was extended both proximally and distally in the line of the quadriceps and patellar tendons, respectively. Although not the standard approach used *in vivo*, the aim was to keep the strength and integrity of the extensor mechanism near constant for each condition tested and, by doing so, avoid confounding from variations in strength of extensor mechanism repair associated with the parapatellar approach. Anterior referencing was used for all three arthroplasty

procedures. The method of surgical implantation for the prostheses followed the manufacturer recommendations.

Each knee was mounted in a kinematic test rig. This rig allowed the tibia to remain unconstrained, permitting passive flexion-extension knee motion. A combined load was applied to the quadriceps muscles and ITB to produce a known quadriceps tension. The extensor moment efficiency was measured across a range of 0° and 120° knee flexion. A pressure sensor was inserted into the patellofemoral joint to measure patellofemoral resultant force, peak pressures and contact area.

Data analysis involved the use of one-way ANOVA and post-hoc paired *t* test for evaluating the four conditions at knee flexion angles between 0° and 120° for all four parameters. The significance level was adjusted to $p < 0.00833$ for comparison of the four conditions to each other.

2.12 Outcome Measures

2.12.1 Measurement of Outcomes

Primary Outcome: Extensor Mechanism Efficiency (EME)

The EME is essentially a ratio of input and output. The definition of EME is the knee extensor moment produced per Netwon of quadriceps tension, that is, the extensor moment (Newton metres, Nm) produced (output) per Newton put in (input).

This measurement was calculated using the following equation:

$$\frac{Force(N) \times Distance(m)}{ConstantForce(N)} = \frac{Nm}{N_{QT}} = EME(Nm / N_{QT})$$

Force (N) is calculated using the force multiplication factor described in section 2.14.5. The distance (m) was constant, set at 0.25m and equated to the distance from the centre of rotation to the point of force application. The constant force was the quadriceps tension kept at 205N load.

In theory, the EME should be high when the resultant force is low because moment efficiency is directly proportional to the extensor moment arm. To confirm this theory and test the hypotheses stated in section 2.8, the following secondary outcomes were measured.

Secondary Outcomes: Resultant force, Peak pressure and Contact area

The resultant force (N), peak pressure (MPa) and contact area (mm^2) were all computed by the Tekscan software used to measure these outcomes as described in section 2.14.3.

2.13 Sample size

Application of a standard formula was not feasible as a number of factors were unknown, such as the population means, potential varying standard deviations for each group at each angle of knee flexion due to the replication factor and the variation in clinically relevant (meaningful) differences in extensor moment efficiency (and other secondary outcomes) between the groups. Thus the 'expected' data needs to be estimated. In general, there are three ways in which the means and standard deviations could have been guesstimated:

1. A review of relevant literature
2. A pilot study
3. Cohen's effect size guidance (the difference of two group means divided by the pooled standard deviation).

The first option was chosen for this current study.

At the time of designing this study there were no published studies that could have been used to indicate estimated means of extensor mechanism efficiency, standard deviations or effect size. However, previous studies that used a similar experimental set up (rig) to the current study, had reported the use of sample size calculations. These cadaveric biomechanical studies performed power calculations which showed eight knees would allow identification of significant change in

extensor mechanism length: 2.1mm medial patellofemoral ligament and 4.4mm lateral retinaculum (Ghosh *et al.*, 2009), change of patellar lateral translation of 7mm (Stephen *et al.*, 2013) and change of femoral translation and of rotation of approximately 2.1mm and 1.2° with 95% confidence and 80% power (Kondo *et al.*, 2011). None of these investigations stated the standard deviation used however this was determined using the information provided. In order to utilise this information, the following assumption was made:

> The 'behaviour' of the data and the degree of change deemed as clinically relevant in these studies is proportional to the amount of change that is likely to be of clinical importance in extensor moment efficiency variance between the conditions assessed in the current study.

Based on this assumption, using the sample size data in the Stephen *et al.* (2013) study and setting the significance level, α, at 0.05 and the power, β, at 80%, the following equation was applied:

$$n = \frac{(t_{\alpha/2} + t_{\beta})^2}{\delta^2}$$

$$\delta = \frac{\Delta^2}{\sigma^2}$$

α = 0.05

β = 0.80

$t_{\alpha/2}$ = 2.365

t_{β} = 0.896

σ^2 = 6^2 (This standard deviation was calculated using PS – Power and Sample Size Calculations, software, version 3.0.0043, (Dupont & Plummer, 2009))

Δ^2 = 7^2

$$n = \frac{(2.365 + 0.896)^2}{\left(\frac{7}{6}\right)^2}$$

$$n = \frac{10.634}{1.361}$$

n = 7.813

n ≅ 8

The anticipated effect size:

$$\theta = \frac{\mu_1 - \mu_2}{\sigma}$$

$$\theta = \frac{7}{6}$$

$$\theta = 1.16\dot{6}$$

Once the results of the current study were obtained, the actual effect size(s) were calculated to demonstrate whether the chosen sample size of 8 was the appropriate sample size to use.

2.14 Methodology

2.14.1 Materials: Specimens and Preparation

Ten fresh-frozen human cadaveric knees with intact soft tissue envelope and knee ligaments were used. These were obtained from University Hospitals Coventry and Warwickshire (UHCW) NHS Trust. This trust had acquired these cadaveric knees from Science Care (Phoenix, Arizona, USA), a tissue bank accredited by the American Association of Tissue Banks (AATB) and Accreditation Council for Continuing Medical Education (ACCME). This organisation is responsible for screening the donors and obtaining consent for donation for training and professional education and medical research use. A Material Transfer Agreement was established between the two sites and the cadaveric knees were securely

transported from UHCW NHS Trust Surgical Training Suite to the Biomechanical Engineering Laboratory at Imperial College London. Each knee was allocated an assigned number for tracking purposes from the point of lab entry to disposal. The knees were stored at -20°C until time of use, when they were transferred to a designated refrigerator for 24 hour for thawing. Normal saline was used to maintain moisture of the knees. The kinematic experiments were performed the following day once thawing was complete.

Two cadaveric knees were used to finalise the methodology. The demographics of the remaining 8 cadaveric knees consisted of: 5 male (2 right, 3 left) and 3 female (1 right, 2 left) with a mean age of 74.6 years (61-82). The results of these eight knees were used for data analysis.

All ten cadaveric knees were devoid of macroscopic arthritis; this was initially confirmed using radiographs- lateral, anteroposterior and skyline views and further on dissection. In addition, none of the cadaveric knees had any other anatomical defects or undergone previous knee surgery. The skin and subcutaneous adipose tissue were excised from each knee and dissection was performed. The muscle, knee capsule, ligaments, quadriceps, patellar tendon and iliotibial band (ITB) remained intact. The quadriceps was separated into six components: rectus femoris (RF), vastus intermedius (VI), vastus lateralis longus (VLL), vastus lateralis obliquus (VLO), vastus medialis longus (VML) and vastus

medialis obliquus (VMO). The distal tendinous fibres of the muscles are usually merged and were therefore left intact to ensure the actions of the muscles were as physiological as possible.

Approximately 20cm of femur proximal to the knee joint and 15cm of tibia distally were preserved. Intramedullary rods were inserted and fixed with polymethylmethacrylate (PMMA) bone cement into the tibia to extend it distally and the femur to aid attachment to the rig.

2.14.2 Apparatus

Rig Design

The basic structure of the rig had previously been designed and constructed (Stephen *et al.*, 2013). This construct consisted of two black Perspex sheets mounted parallel to one another on a flat MDF (medium-density fibreboard) surface. The base of each sheet was bolted to the MDF with polyethylene reinforcements. The Perspex sheet to which the strain gauge device was attached was reinforced on both sides, framing the base and distal halves of the front and back edges; only the outer aspect of the other sheet was reinforced. The polyethylene frame increased the rigidity and had a sliding mechanism that allowed height adjustments to be made to the Perspex sheet if required (see Figure 2-7).

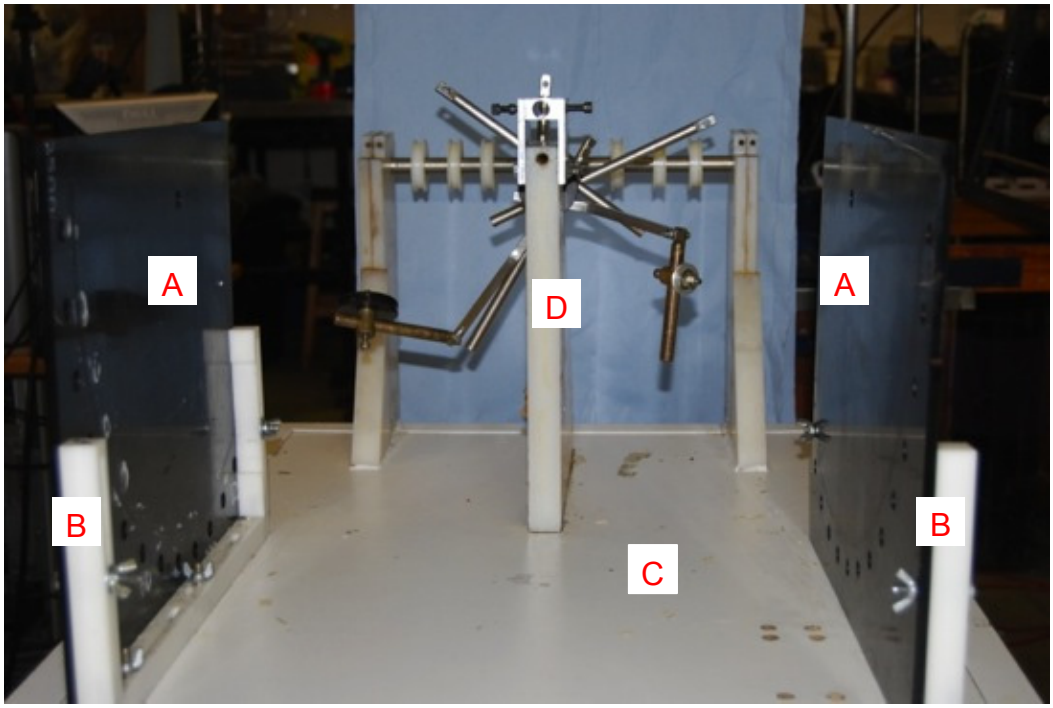


Figure 2-7 Rig without crank mechanism

A Perspex sheets with 10° increments from 0° to 120°

B Polyethylene reinforcements to increase rigidity and allow for height adjustments

C MDF base

D Knee mount aspect of rig: polyethylene block with adjustable metal block, angled metal rods and upper pulley system

The Perspex sheets were connected by a crank device that consisted of two parallel high-density plastic arms linked by a perpendicular steel rod via bolts (see Figure 2-8 and Figure 2-9).

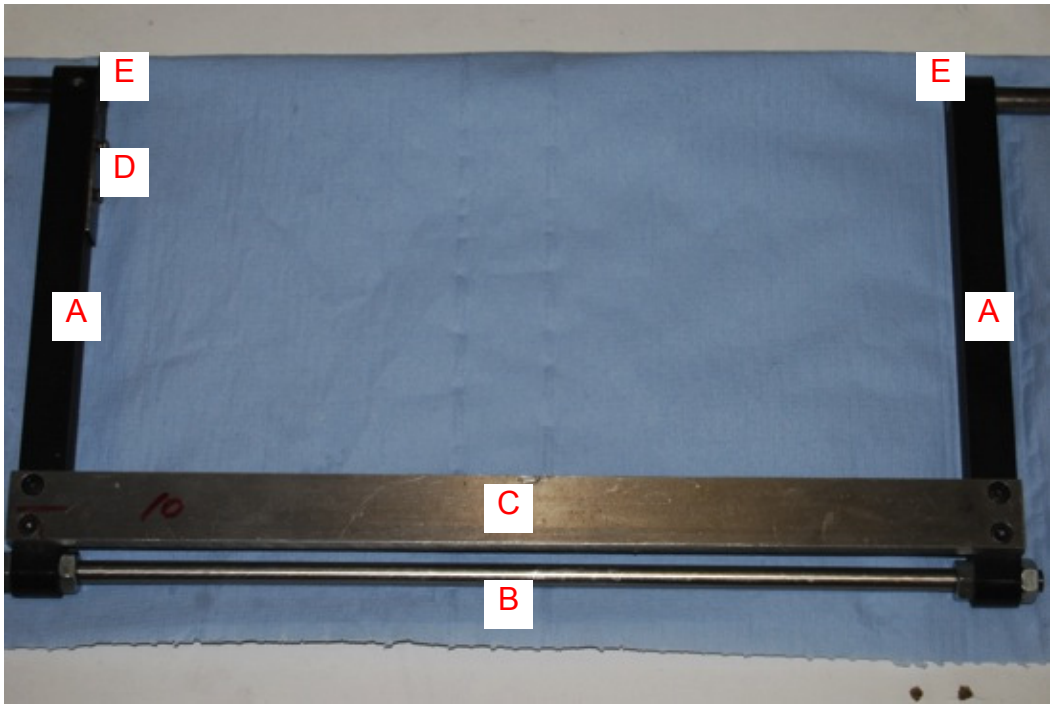


Figure 2-8 Crank device

A High-density plastic arms

B Horizontal metal rod

C Aluminium bar reinforcing metal rod, reducing torque in the system

D Stainless steel sheet reinforcement to reduce torque

E Pivot point of crank mechanism

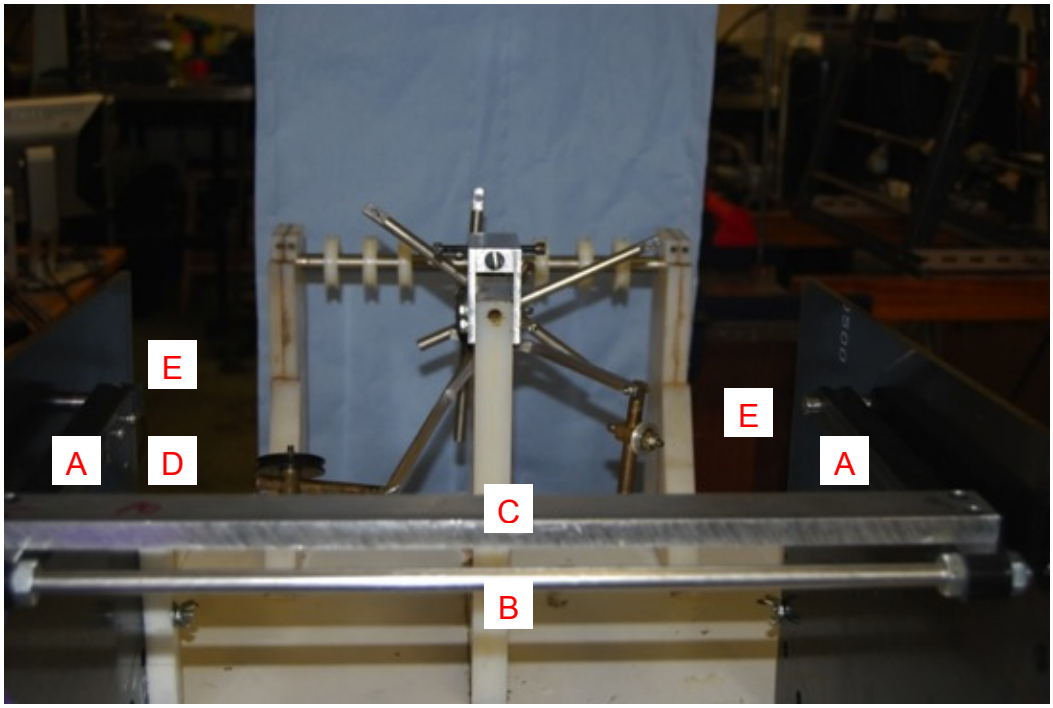


Figure 2-9 Crank device attached to rig

A High-density plastic arms

B Horizontal metal rod

C Aluminium bar reinforcing metal rod, reducing torque in the system

D Stainless steel sheet reinforcement to reduce torque

E Pivot point of crank mechanism

The knee mount aspect of the rig consisted of a polyethylene block with a height adjustable metal block fixed to the MDF base equidistance from each Perspex sheet (see Figure 2-7). The metal block had a central tunnel to accommodate the femoral rod. The rod position was adjustable within the central tunnel, allowing for the epicondylar axis of the knee (centre of rotation) to be aligned with the axis of the strain gauge-crank mechanism. The femoral rod was secured within the tunnel with four bolts to prevent rotation (see Figure 2-10).

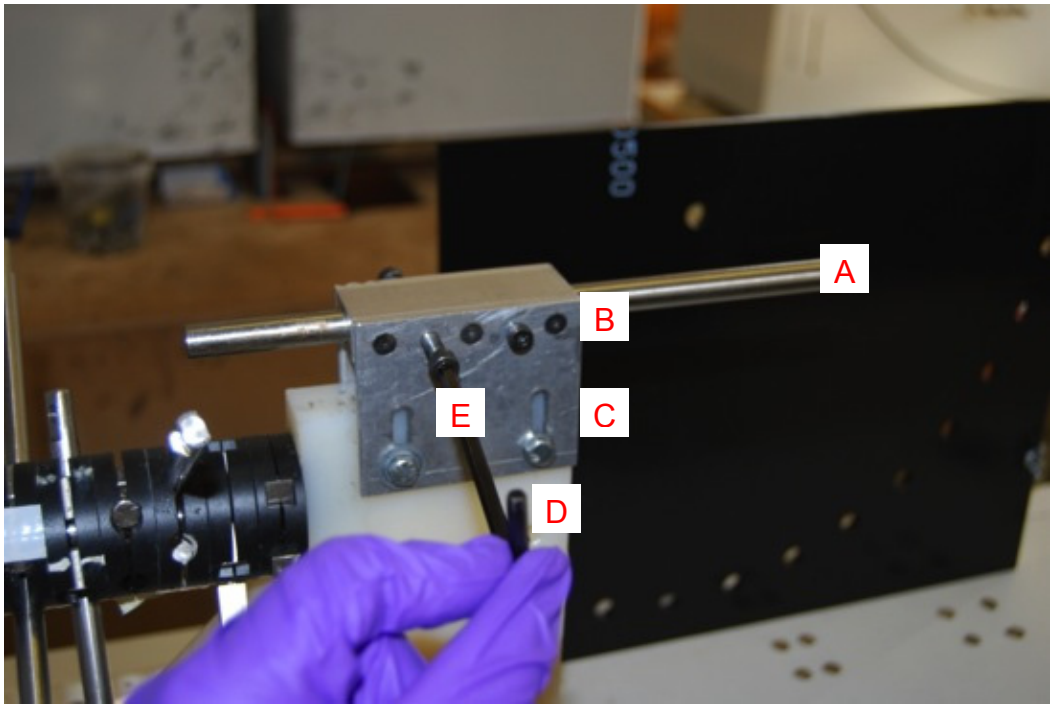


Figure 2-10 Knee mount aspect of rig: adjustable metal block with central tunnel to accommodate femoral rod

A Femoral intramedullary rod

B Central tunnel in metal block to accommodate femoral rod

C Adjustable metal block to aid alignment of the epicondylar axis with the pivot point of the crank mechanism

D Polyethylene block base securing adjustable metal block and posterior black plastic discs

E Four securing bolts to fix intramedullary rod and prevent rotation within the tunnel

Attached to the posterior aspect of the polyethylene block were multiple high-density plastic black disc skewered on a pitched rod which was bolted to the pulley mechanism. Steel rods were interposed between the plastic discs at fixed angles that replicated those existing in the quadriceps muscles. A rod with a pulley was also interposed to accommodate the iliotibial band (ITB) (see Figure 2-11).

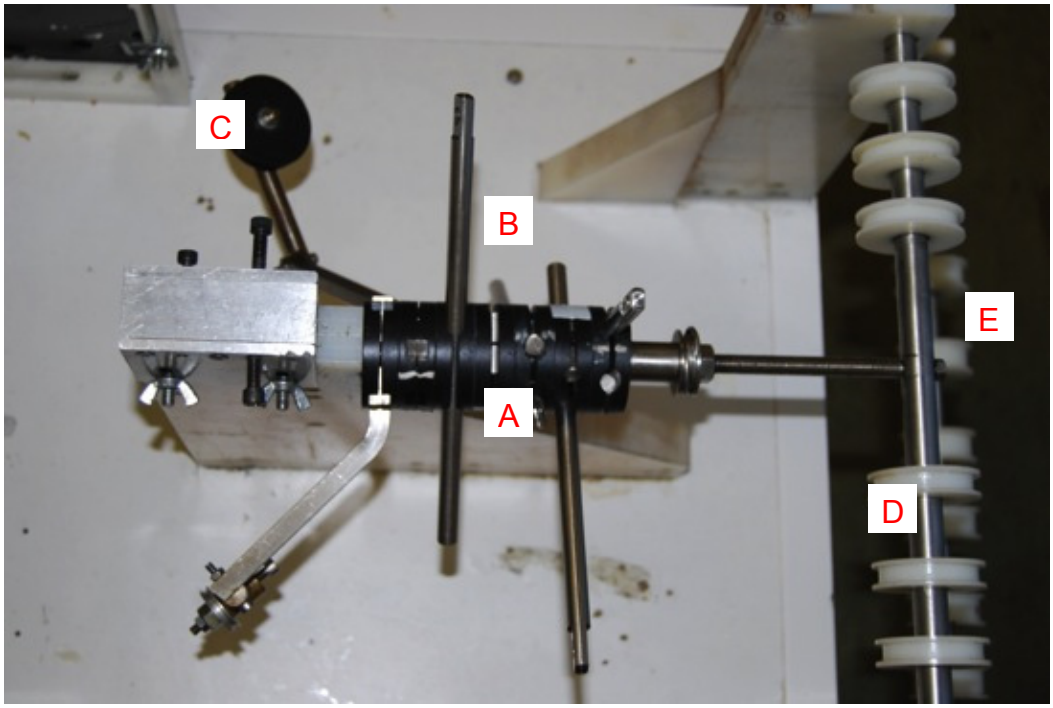


Figure 2-11 Steel rod interposition to replicate individual quadriceps muscles and ITB direction of pull

A Black plastic discs

B Interpositioned metal rods placed in the physiological direction of pull

C Rod with pulley for ITB

D Upper pulley system

E Lower pulley system

Each angled rod had a squared-off end with a hole to accommodate the rope attached to the corresponding part of the quadriceps. Each rope was tensioned with the corresponding load via individual pulleys, which were situated a fixed distance behind allowing for adequate excursion of each rope. The pulleys were positioned along the perpendicular bar bolted to the pitched rod (see Figure 2-12 and Figure 2-13).

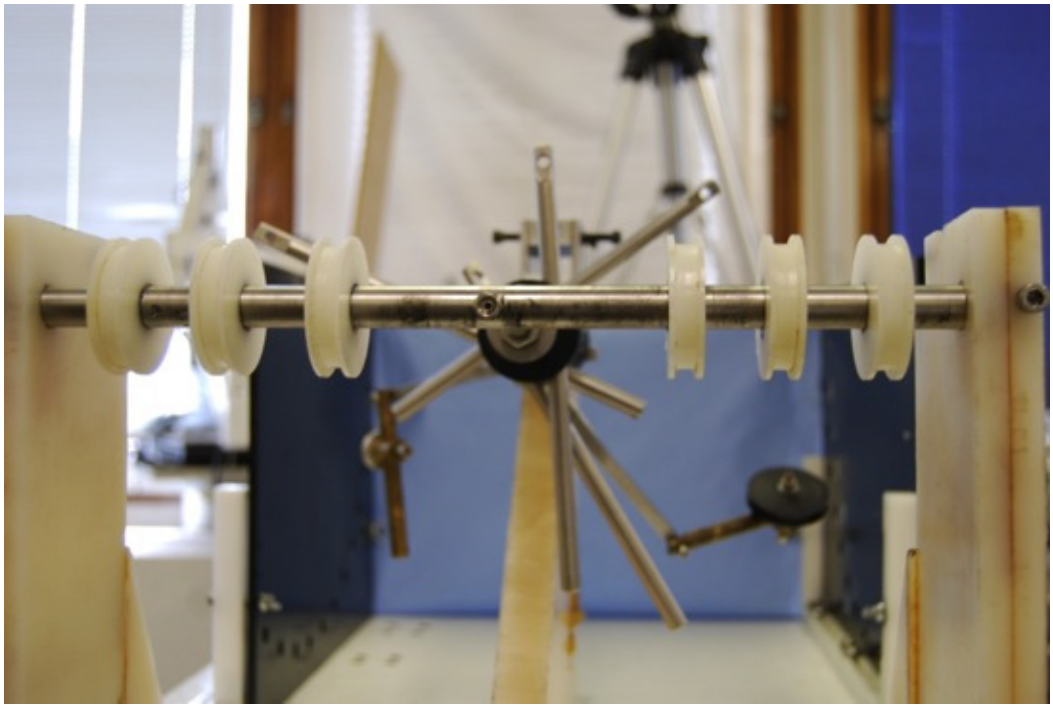


Figure 2-12 Upper pulley system

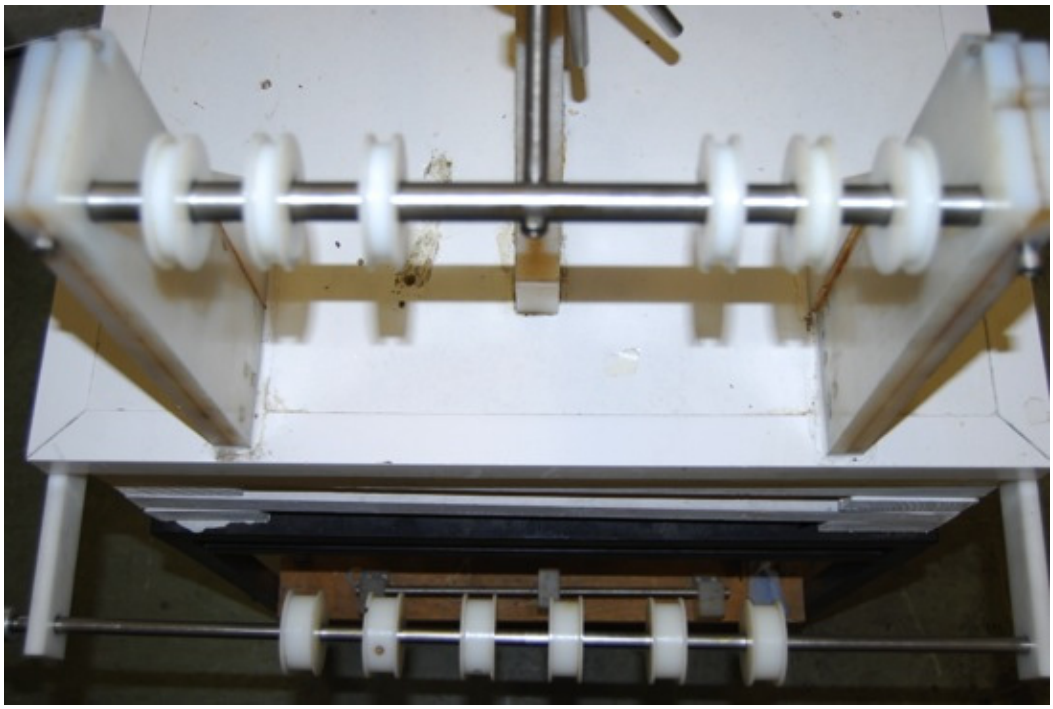


Figure 2-13 Lower pulley system

The plastic black discs were adjustable, allowing for the angle of the rods to be altered depending on whether a left or right knee was mounted (see Figure 2-10). The load for each muscle was suspended from the end of each rope. Each point of rotation was lubricated to ensure smooth continuous motion without seizing in the system or wear to the components.

Rig Design Modifications

Following testing, with two methodology knees, the rig underwent minor modifications to meet the demands of the current experimental set-up:

1. A thin sheet of stainless steel was required to reinforce the crank mechanism to reduce the torque (see Figure 2-14).
2. In order to balance the crank lever the clockwise torque of the crank lever was balanced with a rod and larger metal disc counter clockwise torque (see Figure 2-15).
3. An aluminium bar was fixed above and parallel to the rod of the crank. This enabled contact with the tibial rod throughout the whole range of flexion (see Figure 2-8 and Figure 2-9).

Overall, these modifications made the construct more rigid and balanced, thus increasing the threshold for deformation to occur.

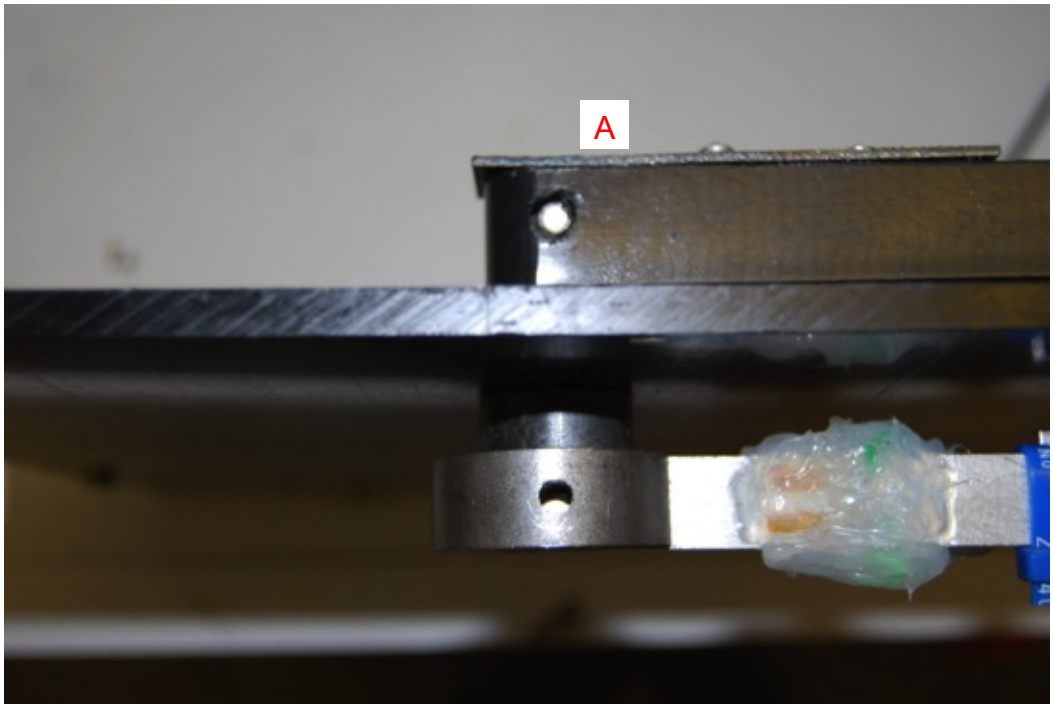


Figure 2-14 Stainless steel reinforcement to reduce torque

A Thin stainless steel strip secured with two screws

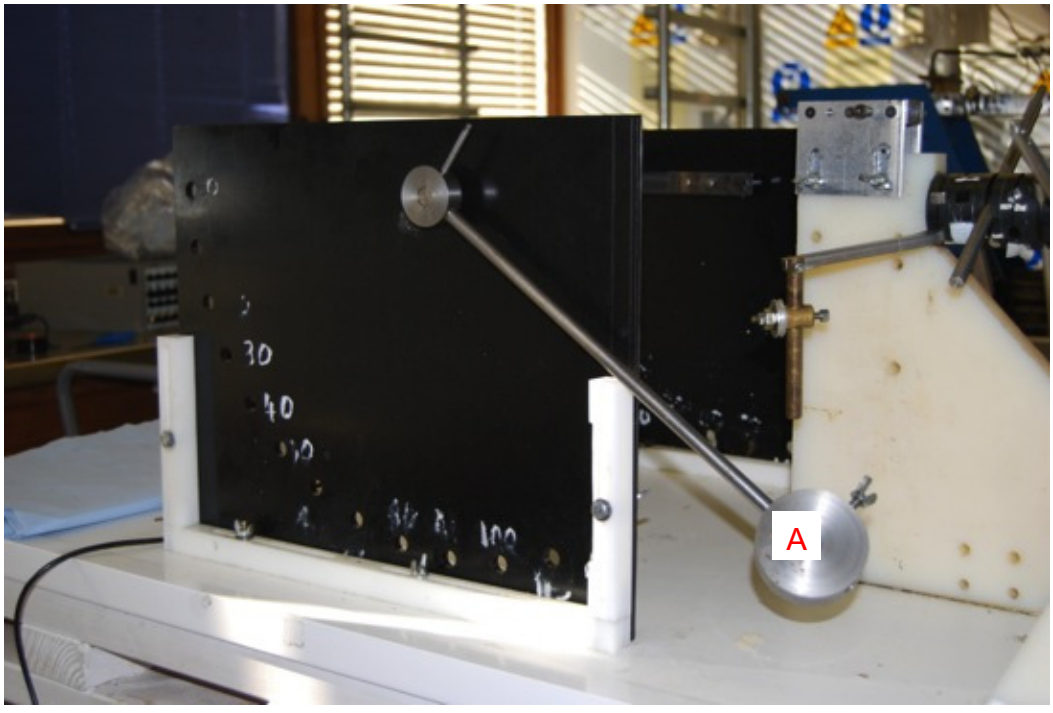


Figure 2-15 Crank Counter lever

A Rod and cylinder counter lever

Knee Mounting

Figure 2-16 shows a knee mounted in the rig. The six individual muscles of the quadriceps and the ITB were bound in cloth and rope (Bull *et al.*, 1999). Hanging weights were attached to each of the seven components via the rope and aligned by the upper and lower pulley system demonstrated in Figure 2-12 and Figure 2-13, respectively. The total load of 175N was applied to the quadriceps and 30N to the ITB, therefore a total of 205N was used. The total load chosen was based on previous studies that used similar experimental set-ups and did not experience tearing of the muscles with this degree of tension (Christoforakis *et al.*, 2006; Farahmand *et al.*, 1998b; Merican & Amis, 2009; Senavongse & Amis, 2005). The distribution of tension applied to the quadriceps was determined in accordance with the physiological cross-sectional area of each muscle (Farahmand *et al.*, 1998a). The cross-sectional areas of each muscle, physiological direction of load in relation to the femoral axis (the orientation of pull of the muscle) and the assigned load attached are listed in Table 2-3.

Table 2-3 Quadriceps physiological cross-sectional area and proportional tension distribution

Muscles and ITB	Cross-sectional Area (%)[a]	Angle of Orientation (°)	Assigned Load (N)
RF	15%	0° lat, 0° ant	26.25N
VI	20%	0° lat, 0° ant	35N
VLL	33%	14° lat, 0° ant	57.75N
VLO	9%	35° lat, 33° post	15.75N
VML	14%	15° med, 0° ant	24.5N
VMO	9%	47° med, 44° post	15.75N
ITB	-	0° lat, 6° post	30N

[a]As a percentage of total quadriceps muscle

The epicondylar axis was aligned with the attachment points of the crank mechanism. The Tekscan sensor was attached to the Tekscan handle seen balancing on a rectangular box on the right. Blue nylon sutures securing the sensor in place are visible on the lateral aspect of the knee (labelled D).

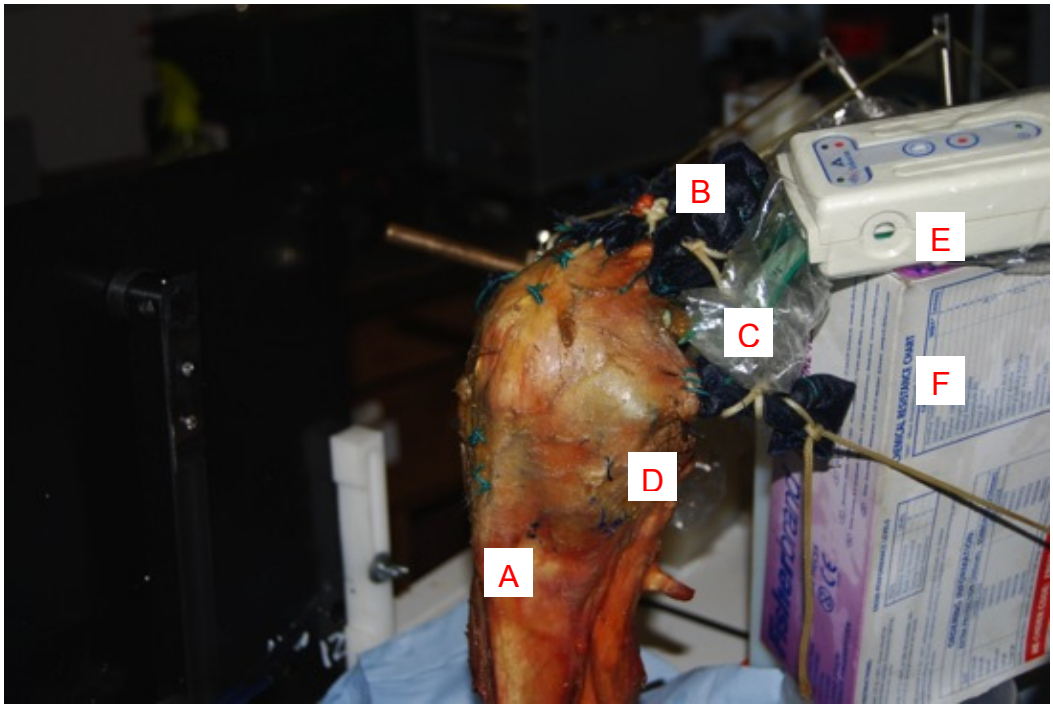


Figure 2-16 Knee mounted in rig

A Cadaveric knee

B Individual muscles and ITB bound in clothe and rope tensioned in physiological direction of pull. Rope inserted through eyelet type entry points of each metal rod

C Tekscan sensor tab visible, matrix part of sensor inserted into patellofemoral joint

D Nylon sutures used to secure Tekscan sensor in place visible on medial aspect of knee

E Tekscan handle hardware with tab of sensor inserted. Handle protected in transparent polyethylene bag to avoid fat or fluid entering the device

F Box stabilising and supporting weight of Tekscan handle hardware

Patellofemoral resultant force, peak pressure and contact area measurements

Tekscan versus Fuji Film

Bachus *et al.* (2006) performed a study aimed at determining the performance and accuracy of Fuji Film compared with Tekscan Sensor System. Two methods of calculating parameters using Fuji Film were tested: Erase Method and Threshold Method. The Erase Method involves deleting pigmented areas suspected to be outside the boundary of the pressure stain. The Threshold Method consists of predetermining a binary colour gradient whereby the pixels are highlighted white or black based on the extent of pigmentation detected. The number of coloured pixels on the Fuji Film is digitally analysed by programmed computer software once the film has been calibrated. The investigation involved application of known loads producing known contact areas, forces and pressures to the materials. The measured values of each parameter were compared with the known values to quantify the accuracy of the systems. The authors defined the acceptable degree of data variation as ±5%. The results of this study are summarised in Table 2-4 to Table 2-9.

Table 2-4 Accuracy of contact area measurements at lowest applied loads

Material	Overestimation	Underestimation	Difference	Statistically Significant
Fuji Film Erase Method			1%	N
Fuji Film Threshold Method			27%	Y Loads < 3375N
Tekscan			2%	N

Table 2-5 Accuracy of contact area measurements at highest applied loads

Material	Overestimation	Underestimation	Difference	Statistically Significant
Fuji Film Erase Method			7%	Loads > 2375N
Fuji Film Threshold Method			2%	Loads < 3375N
Tekscan			3%	N

Table 2-6 Accuracy of force measurements at lowest applied loads

Material	Overestimation	Underestimation	Difference	Statistically Significant
Fuji Film Erase Method			4%	N
Fuji Film Threshold Method			4%	N
Tekscan			2%	N

Table 2-7 Accuracy of force measurements at highest applied loads

Material	Overestimation	Underestimation	Difference	Statistically Significant
Fuji Film Erase Method		□	2%	N
Fuji Film Threshold Method		□	13%	N
Tekscan	□		3%	N

Table 2-8 Accuracy of pressure measurements lowest applied loads

Material	Overestimation	Underestimation	Difference	Statistically Significant
Fuji Film Erase Method	□		4%	N
Fuji Film Threshold Method	□		41%	Loads < 2375N
Tekscan	□		2%	N

Table 2-9 Accuracy of pressure measurements highest applied loads

Material	Overestimation	Underestimation	Difference	Statistically Significant
Fuji Film Erase Method		□	9%	Loads ≥ 1875N
Fuji Film Threshold Method		□	5%	Loads < 2375N
Tekscan	□		4%	N

The results clearly demonstrate the Fuji Film produces a higher degree of variability than the Tekscan. These findings are also supported by Harris *et al.* (1999). Although all three methods produced accurate and reproducible measurements for applied force, this was not seen on assessment of contact area. Neither the Erase Method nor Threshold Method for Fuji Film results met the acceptable ±5% margin of error for true contact area or pressure.

This study strongly suggests the Tekscan system is a more reproducible, accurate and technically practical system to use than the alternative Fuji Film, irrespective of the analysis method used. Unlike with Fuji Film, no caution need be applied when measuring high or low loads as the variation in accuracy remains below 5%. Other advantages of the Tekscan system are the sensors have a thinner profile than the Fuji Film and data acquisition using the Tekscan system occurs real time *in situ* whereas the Fuji Film does not allow for this due to material design.

Based on these compelling findings, the Fuji film method was not used due to lower reproducibility, accuracy and inability to collect real time data *in situ*.

Tekscan System

The secondary outcomes were therefore all measured via a pressure sensor device placed in the patellofemoral joint, using the Tekscan system (Tekscan, I-Scan™ Version 7.0, Boston, MA).

An individual sensor is made up of two sheets of polyester, each with a configured layer of electrical conductor material. The two sheets are held together with a coating of semiconductive ink separating the configuration of the conductor. Where one conductor on one sheet crosses the conductor of the other sheet a sensing element (sensel) is formed (at a row and column intersection). Application of force results in compression of the ink layer and alters the electrical resistance across a sensing element. This change in resistance is dependent (in part) on the force applied during the calibration process. The sensor is connected to a computer via handle hardware (*Evolution*®, Tekscan Inc., Boston, Massachusetts, USA). The *I-Scan*® software (Tekscan, I-Scan™ Version 7.0, Boston, Massachusetts, USA) allowed for calibration, for recording and analysing data and for converting the measured resistances into estimates of resultant force, peak pressure and contact area.

Based on review of previous studies (Anglin *et al.*, 2010; Brimacombe *et al.*, 2009; Gill *et al.*, 2004; Martinelli *et al.*, 2006; Wilson *et al.*, 2003), the sensor most commonly used to assess patellofemoral joint mechanics was Tekscan sensor model 5051. However, the specific psi (pounds per square inch) or MPa varied considerably between

experiments. To determine the most appropriate sensor a number of 5051 sensors with different MPas were tested.

Sensor Selection

Selecting the appropriate sensor full-scale pressure range required testing of the sensor in the experimental set-up under each condition. Each sensor was loaded in a methodology knee and the Colour Pressure Legend was opened and set from 0 to 255 (Tekscan eight-bit full raw digital output scale). The maximum sensel output is 255 Raw DO (Digital Output). The application pressure should nearly saturate the sensor output. If, under constant load, peak pressure was below the maximal sensel output throughout the range of knee flexion, for example, approximately 240 DO, then this sensor full-scale range was deemed to be the most appropriate. If a sensel reached 255 DO at any point during the range of motion, higher pressures and forces occurring at other points of knee flexion would go undetected as the sensor had already reached full saturation and therefore no greater output would register. The selected sensor full-scale range had to satisfy this requirement under all four conditions. The 5051 pressure sensor, psi 350 (Tekscan, I-Scan™ Version 7.0, Boston, MA) met this criterion and was therefore used to calculate patellofemoral joint reaction force, peak pressure and contact area. The matrix of this sensor was comprised of 1936 sensels, size (w) 55.9mm x (h) 55.9mm x (d) 0.1mm, with a saturation pressure of 2.41MPa.

Sensor Preparation

A new sensor that has not undergone optimisation may lack uniformity and produce a non-linear response to applied force or pressure. Hysteresis (the difference in the sensor output during loading and unloading the same force) and drift (change in sensor output under a constant force over a period of time) are also other sensor characteristics, which if not minimised, can influence the accuracy of the sensor output. Optimisation of a sensor's performance involves three steps: conditioning, equilibration (if required) and calibration.

Conditioning is the repeated loading ('exercising') of a sensor in order to reduce the effects of drift and hysteresis. The sensor is loaded to 120% of the pressure expected during the actual test application. Similar material to that in the test application (native knee and prosthesis) is used during application of pressure.

Equilibration is the normalisation of each sensel output to the mean output of all the sensels on the matrix. This is achieved by applying a known uniform pressure to all the sensels using the Tekscan equilibration bladder. The software determines the scale factor that is applied to each sensel, which results in a uniform output at that pressure. Equilibration is necessary when the sensor is loaded repeatedly in the same region on the sensor. The sensels in this area undergo degradation with time whilst those in the unloaded area remain intact and hold a higher sensitivity level. Equilibration compensates for a calculated decrease in sensitivity over time and provides a more uniform sensor

output (sensitivity). The Tekscan system available did not have an equilibration bladder. Attempting to equilibrate without this bladder may have resulted in unevenly applied pressure and created a bias in the sensor output. In this circumstance, it is more accurate to not equilibrate. Conveniently, equilibration was not deemed essential for this experiment for the following reason. During knee flexion, the points of contact in the patellofemoral joint vary with change in knee angle and test condition (to an extent) thus the area of sensels loaded also varies, minimising the risk of sensor output inaccuracy.

Calibration is the process by which the DO is converted to an actual engineering unit, such as MPa or PSI. Calibration allows for the outputs of the same sensor, under different conditions, to be compared and enables the calibrated outputs of various sensors to be compared. Each sensor was calibrated using an electromechanical load frame designed to test materials in tension or compression (Instron 5565 dual column table top model, High Wycombe, Bucks, UK). The driver system moves the cross head down to apply a pre-defined compressive load on the specimen. A load transducer (load cell), mounted in series with the specimen, measures the applied load. The load cell converts the load into an electrical signal that the control system measures and displays. The control system is via an Instron proprietary software program designed specifically for material testing (BlueHill® 2, Instron, High Wycombe, Bucks, UK).

Two calibrations were performed: native knee and prosthetic conditions. The native knee condition was simulated using 3mm thick silicone rubber with a Young's modulus of approximately 0.7MPa, replicating that found in patellofemoral cartilage (Drewniak *et al.*, 2007; Wilson *et al.*, 2003). A square of silicone rubber measuring 55.9mm x 55.9mm was placed either side of the sensor. The three materials were placed between two flat metal plates and a known compressive load was applied, distributing equal pressure. The prosthetic condition was replicated using 8mm thick ultra-high molecular weight polyethylene and a steel cylinder. Due to the relative stiffness between the metal and plastic, and amount of force applied, the extent of deformation resulting from the conditioning and calibrating was negligible and therefore the type of metal used was not critical (see Figure 2-17 and Figure 2-18). Five conditioning cycles were performed at 120% of the average raw pressure, 5.55MPa. Two-parameter power calibration was performed at 20% and 80% of the expected maximum applied joint pressure- 0.8MPa and 3.2MPa, using the I-Scan V7.0 software. The sensitivity level was adjusted to allow for higher pressures to be measured without reaching saturation. This allowed for readings to be obtained that exceeded the manufacturer listed pressure range. During conditioning and calibration the surfaces were coated with surgical lubricant to reduce shear loads (Teflon).

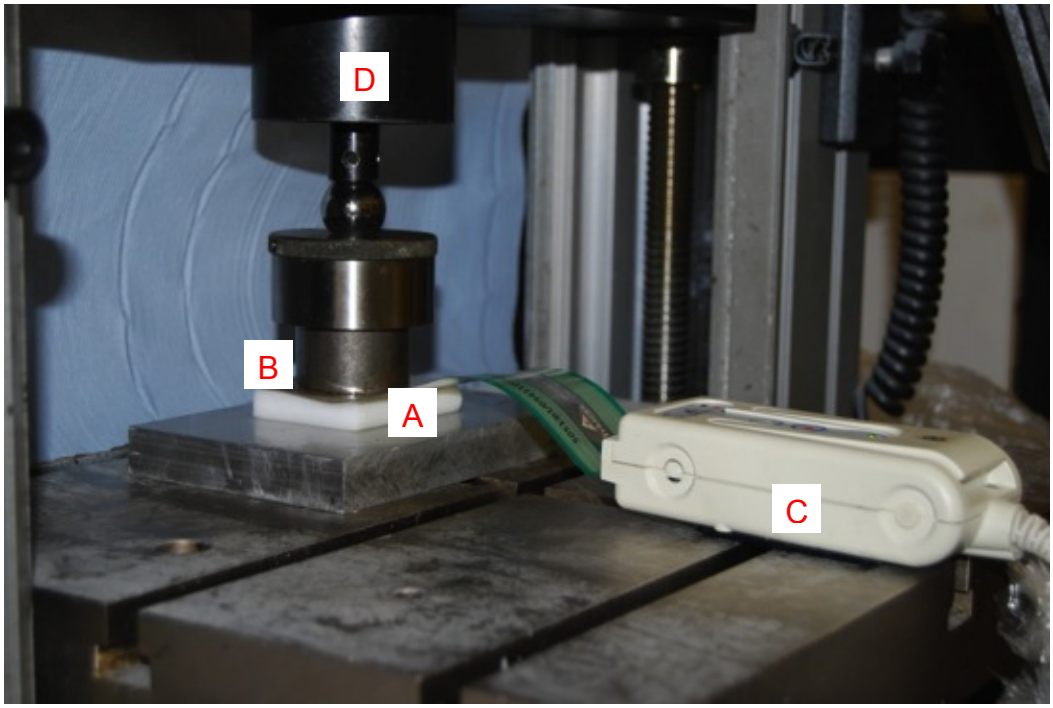


Figure 2-17 Calibration of Tekscan Sensor 1

A Polyethylene

B Metal cylinder

C Tekscan sensor and handle

D Instron load cell device

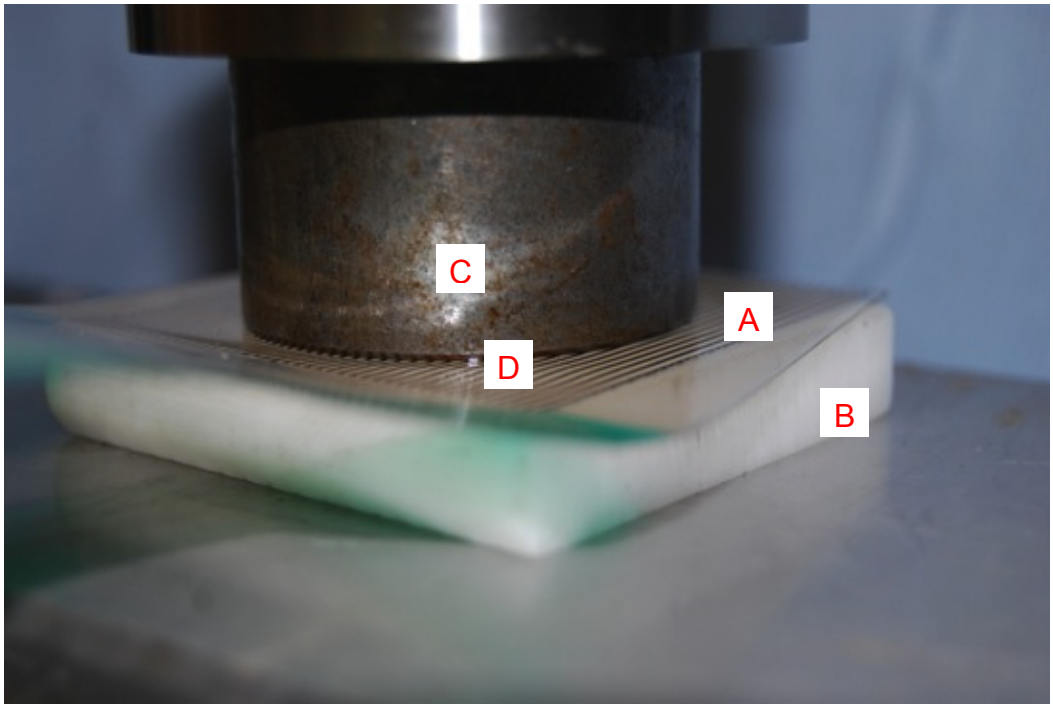


Figure 2-18 Calibration of Tekscan sensor 2

A Sensor matrix; approximate 80% surface area covered

B Polyethylene

C Metal cylinder

D Lubricant between metal-sensor-polyethylene interfaces

For both conditioning and calibrating the load was increased steadily over 5 seconds, held for 10 seconds and reduced to 0.0005N over 5 seconds then left unloaded for 60 seconds. This time frame was similar to that used in each test application in order to minimise the effects of drift. One optimised sensor was used per knee for all four conditions.

Sensor Insertion

Reinforcement duct tape was attached to each side of the sensor, adjacent to but not obstructing the matrix. To the most distal end of each strip of tape, 2'0 Ethilon sutures on a straight 60mm needle (Ethicon™, Somerville, New Jersey, USA) were fastened. These sutures aided in insertion and maintenance of the sensor position within the patellofemoral joint. Only the central quadriceps muscles were raised to insert the sensor into the joint via the suprapatellar pouch, avoiding overstretching of the retinaculum. The needles were passed either side of the patellar tendon insertion, through the soft tissues, pulling the sensor downwards. Once the sensor was positioned in the joint the sutures were tied on the outside at that level, fixing the sensor in place (see Figure 2-19 to Figure 2-21).

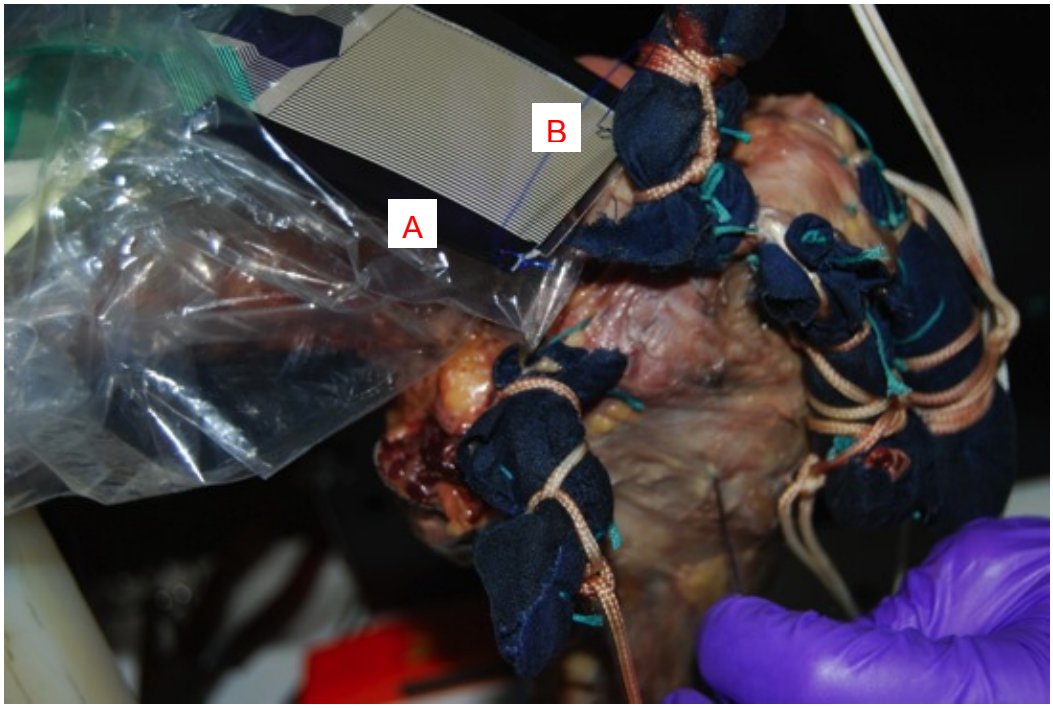


Figure 2-19 Tekscan sensor insertion 1

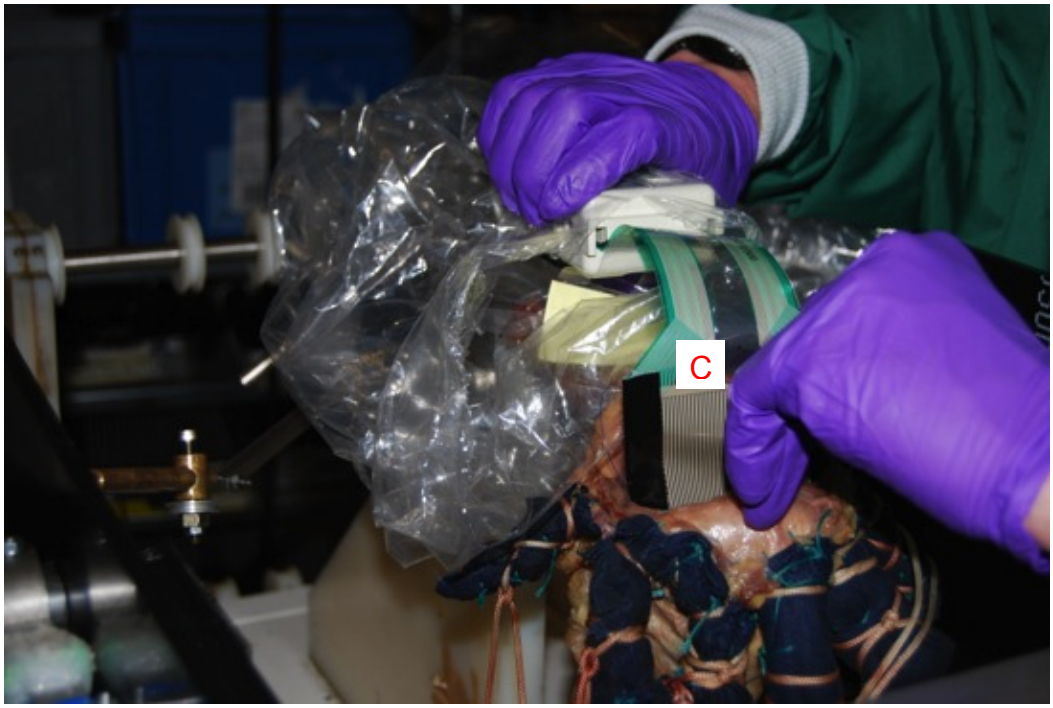


Figure 2-20 Tekscan sensor insertion 2

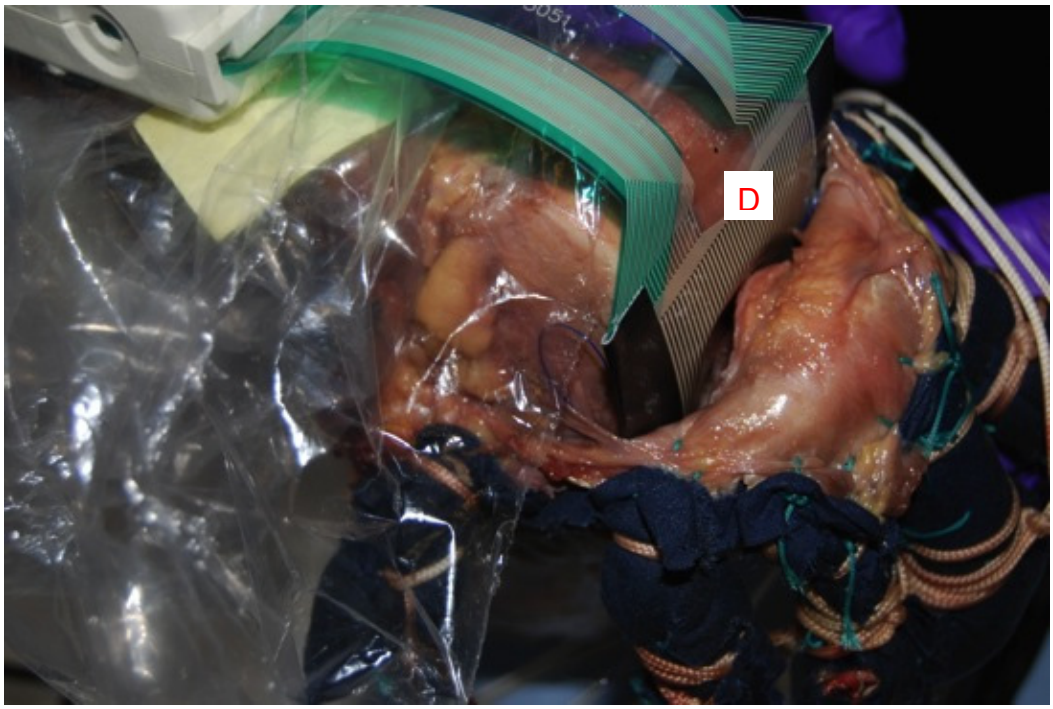


Figure 2-21 Tekscan sensor insertion 3

A Reinforcement duct tape

B Ethilon sutures attached to duct tape to enable anchoring of sensor

C Insertion via the suprapatellar pouch

D Sensor seated centrally within the patellofemoral joint

Data Acquisition

The corresponding calibration file was loaded prior to commencing measuring. Initially, the planned data collection involved measuring at each 10° increment four times under each condition. However, tests with the methodology knees revealed significant sensor degradation. The methodology was therefore modified until sensor degradation was no longer detectable; the number of trials was reduced to two and the increment was increased to 30°. Two to three 0.5mm pin markers were inserted at the level of the superior pole and lateral or medial facet of the patella. Light pressure was applied to the sensor, enough to register on the software system and thus confirm orientation during data analysis (see Figure 2-22 and pin marker location coordinates (18,1) and (33,12) in Figure 2-24). Temperature and humidity readings were taken at regular intervals to monitor changes in the external environment significant enough to impact the behaviour of the sensor and ultimately the data.

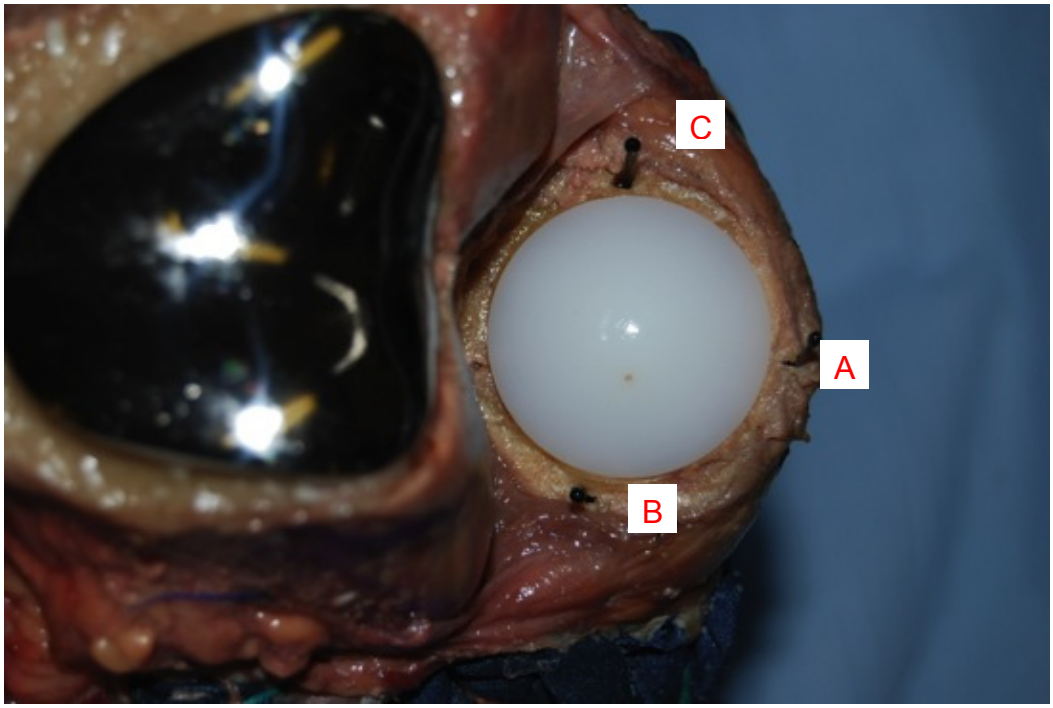


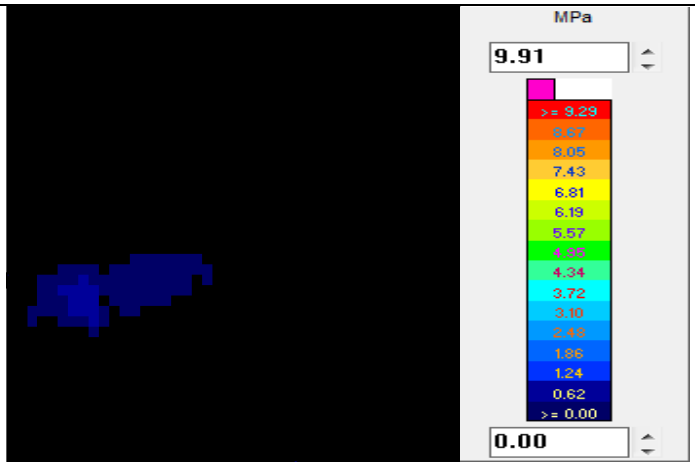
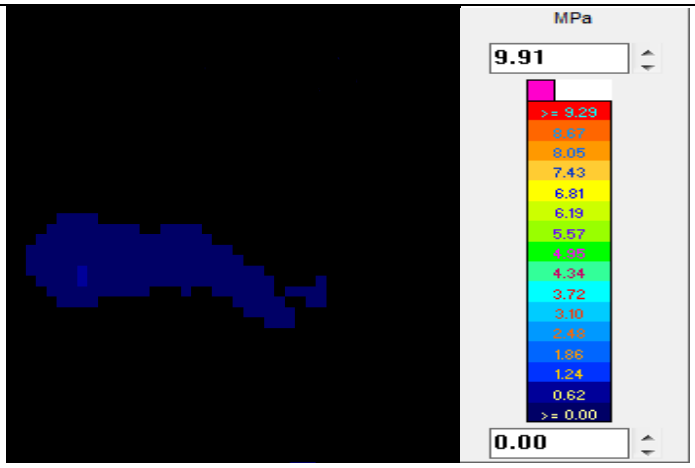
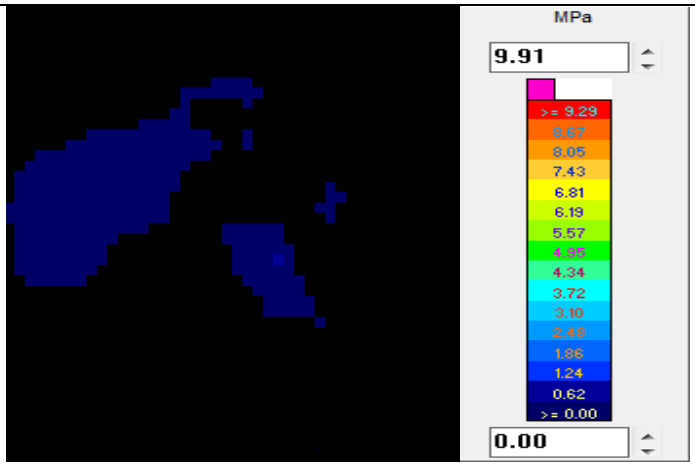
Figure 2-22 Pin markers for patellofemoral joint orientation

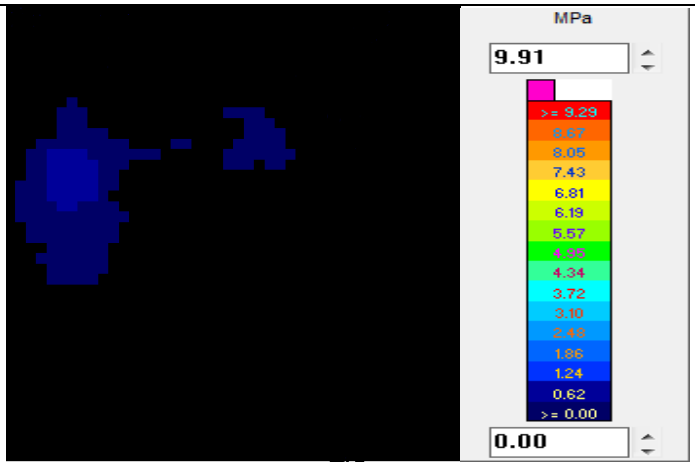
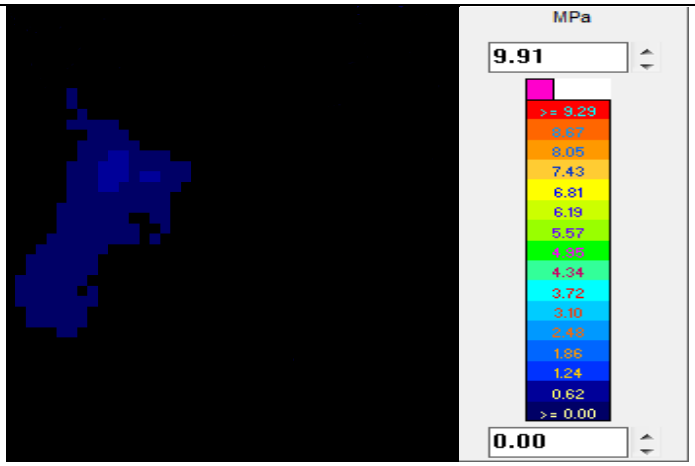
A Superior pole marker

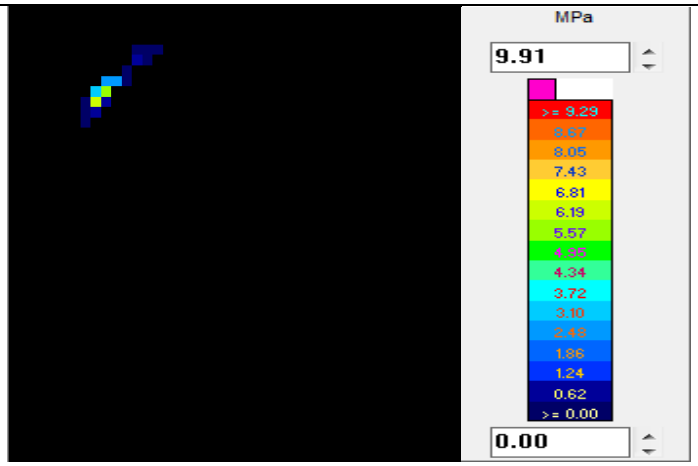
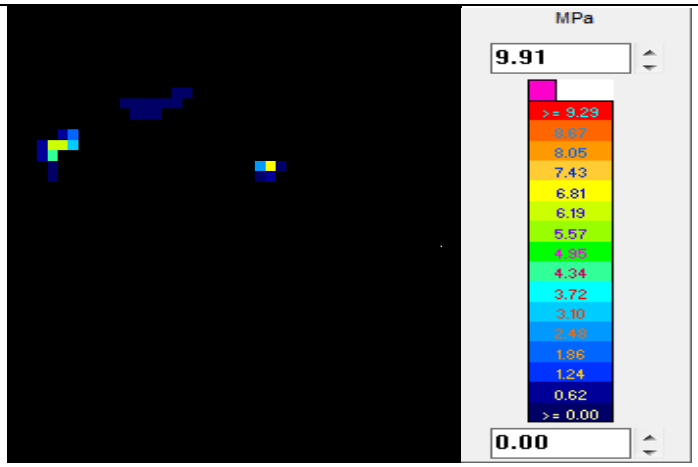
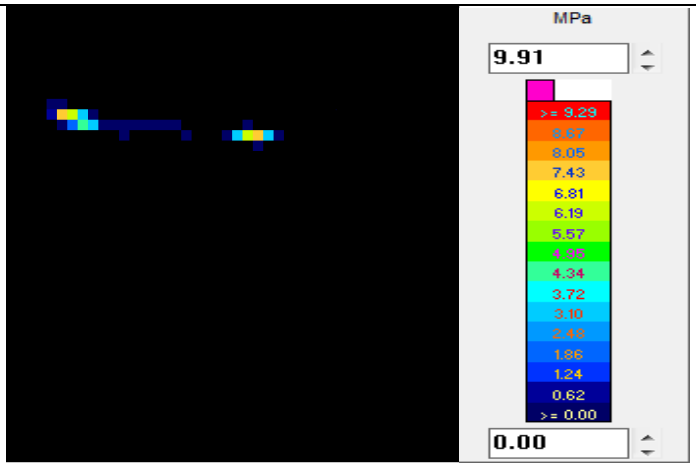
B Medial facet marker

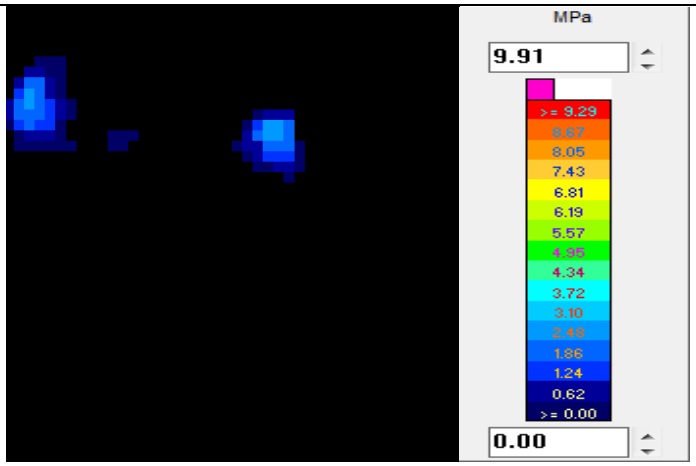
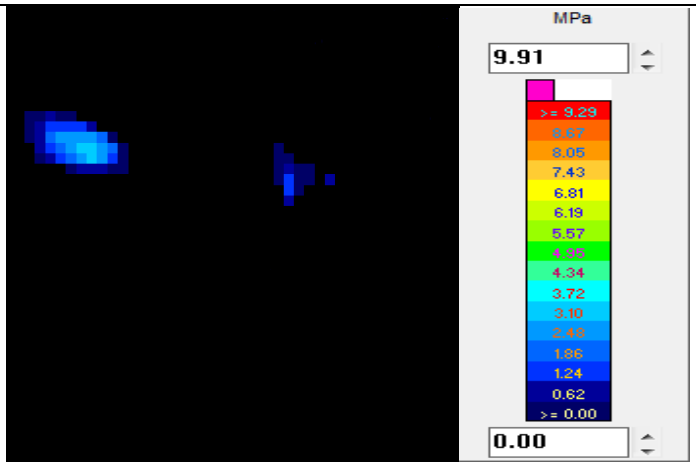
C Lateral facet marker

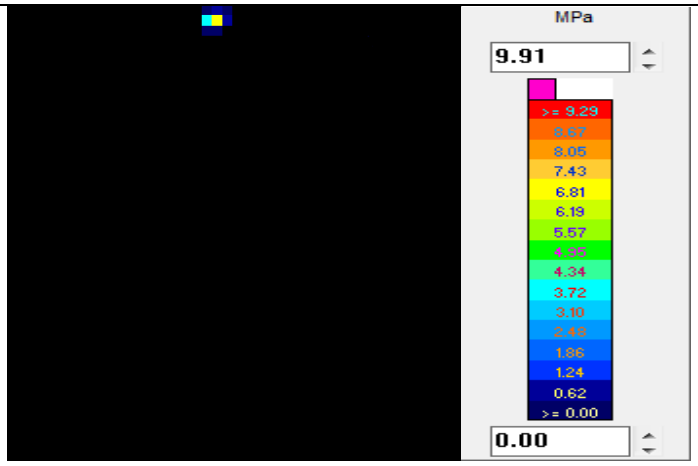
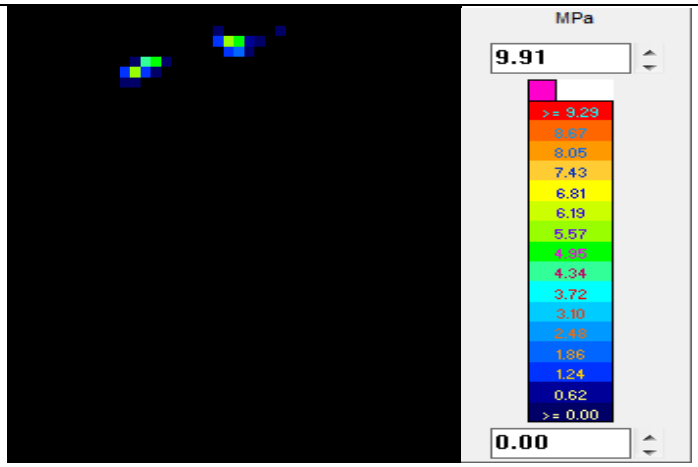
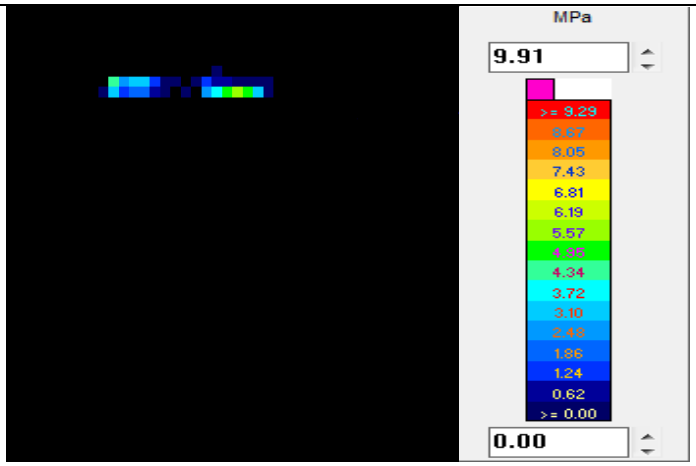
At each angle for each condition a movie data file was generated as shown in Figure 2-23. This movie file was duplicated and saved using a higher sensitivity setting in order to detect the markers.

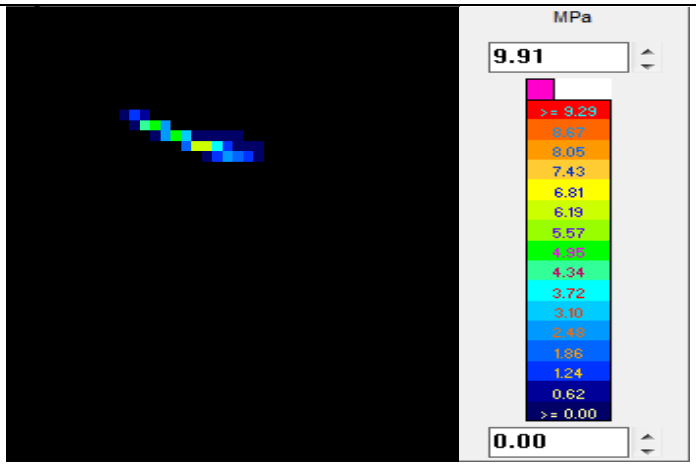
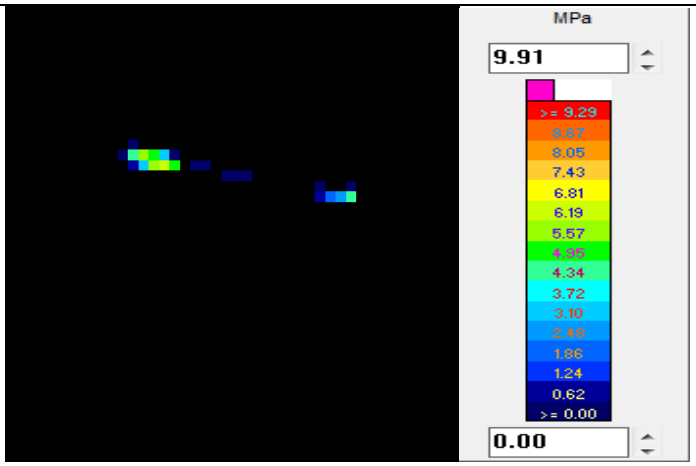
0° NATIVE	
30° NATIVE	
60° NATIVE	

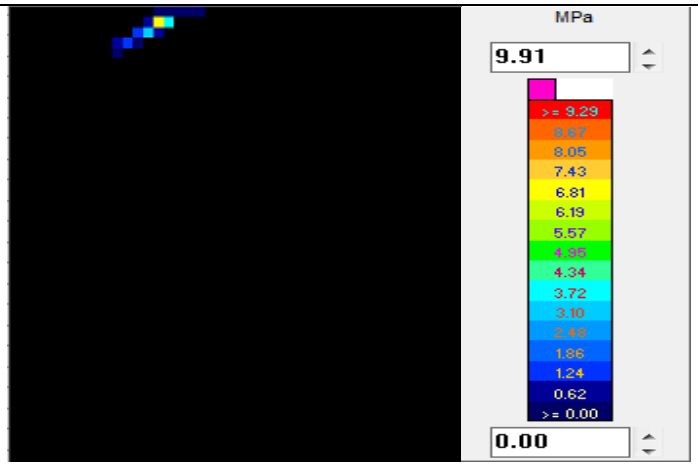
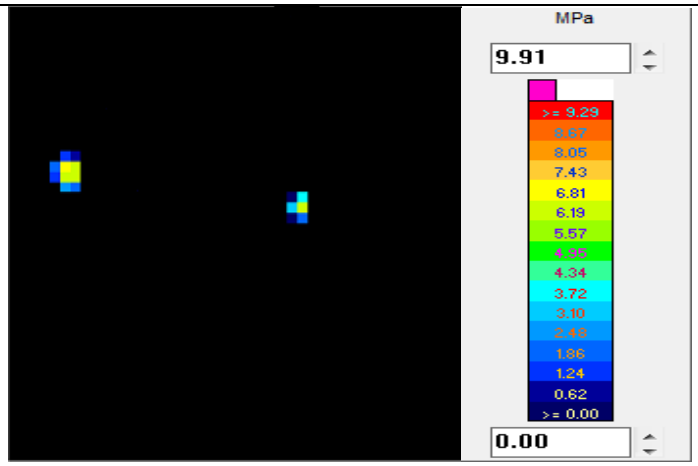
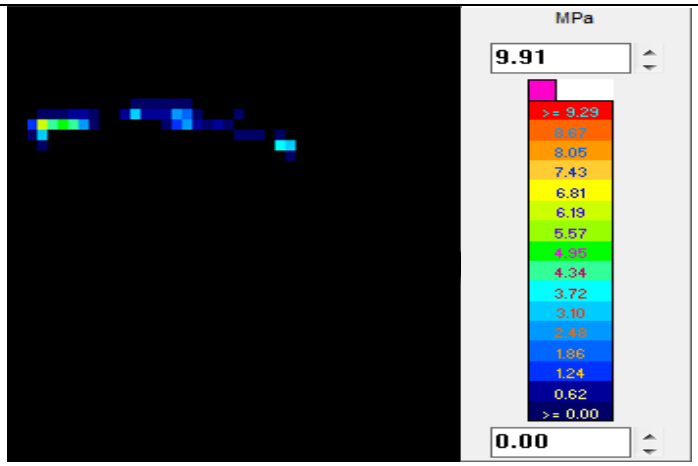
90° NATIVE	
120° NATIVE	

0° PFA	
30° PFA	
60° PFA	

90° PFA	
120° PFA	

0° CR-TKA	
30° CR-TKA	
60° CR-TKA	

90° CR-TKA	
120° CR-TKA	

0° PS-TKA	
30° PS-TKA	
60° PS-TKA	

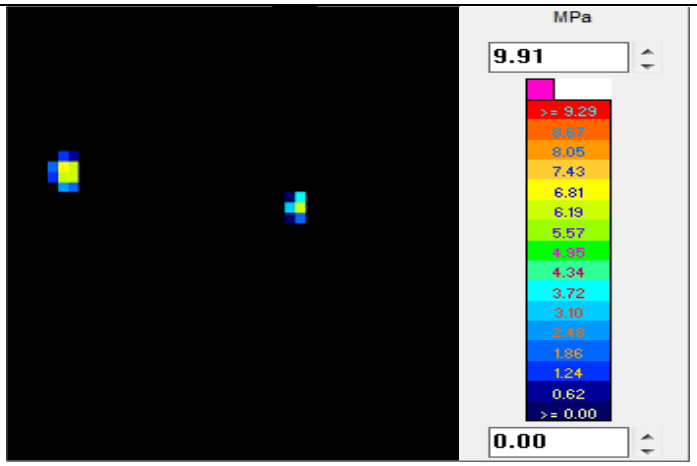
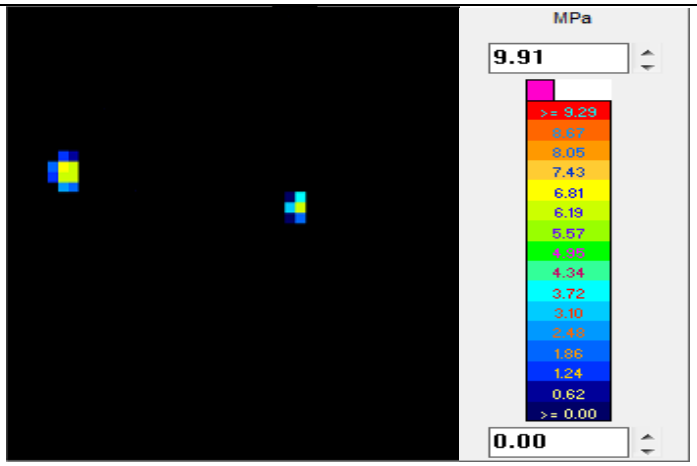
90° PS-TKA	
120° PS-TKA	

Figure 2-23 Movie files at 0°, 30°, 60° 90°, 120° of knee flexion for each condition

Left or right	LEFT
Knee	MO10
Condition	PFA
Flexion Angle	90
Trial	1
Sensel Area (mm2)	1.6129
Date Recorded	06/05/2012
Saturation Pressure (MPa)	9.90804
Total Contact Area (mm2)	138.7094
Peak Pressure (MPa)	2.79
Real Peak (MPa)	2.79

% of Real Peak	90%	80%	70%	60%	60%
	2.511	2.232	1.953	1.674	1.674
Area at % +	9.6774	14.516	22.58	25.81	19.35
Force (N)	141.95133				

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44
1																																												
2																																												
3																																												
4																																												
5																																												
6				0.09	0.07	0.07																																					
7			0.88	0.88	0.52	0.2																																						
8		0.82	2.02	2.16	1.2	0.11																																						
9		1.74	2.68	2.16	1.2	0.41																																						
10	0.82	2.06	2.79	2.16	1.7	0.66	0.13																																					
11	0.88	2.09	2.42	1.91	1.56	0.69	0.11																		0.15	1	1.03	0.64																
12	0.28	1.5	1.91	1.4	1.43	0.46																		0.23	1.56	2.57	2.53	1.95																
13		0.25	0.64	0.64	0.82	0.18					0.11	0.38	0.2											0.88	1.88	2.6	2.72	2.42																
14		0.13	0.13	0.46	0.33	0.11	0.07				0.2	0.07											0.09	0.64	1.23	2.02	2.38	1.91	0.09														
15																								0.35	0.79	1.26	1.77	1.43	0.2															
16																									0.23	0.52	0.94	0.75	0.18																
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Figure 2-24 Example ASCII file

This ASCII file illustrates the patellofemoral contact areas at 90° of knee flexion. The variation in colour represents the different contact pressures (green low, red high). The numbers within each cell are the pressure readings measured in MPa. The pink cells, co-ordinate locations 18,1 and 33,12, represent the patellar superior and medial borders, respectively.

2.14.3 Measurements: Patellofemoral Force, Peak Pressure & Contact Area

The movie file was also saved as an ASCII (American Standard Code for Information Interchange) file and then converted to an excel file via a macro as shown in Figure 2-24. The macro file was coded to enable automatic input of data, already acquired by the Tekscan software, into the excel file. This included all three parameters: contact area (mm^2), pressure (MPa) and force (N). In addition, the macro was programmed to calculate percentage peak pressure achieved to assist with detecting spurious results. All data that appeared to be spurious were deleted. A conservative approach was taken in order to avoid deleting genuine contact areas.

2.14.4 Prosthesis Implantation

A previously validated patellar splitting (transpatellar) approach was used to ensure the integrity of the extensor mechanism remained equal between conditions. This reduced the number of confounding factors such as variation in suture tensioning affecting the extensor retinaculae length changes following closure of a standard medial parapatellar approach.

The initial part of the transpatellar approach involved preparing two holes for accurate screw fixation following splitting of the patella (see Figure 2-25 and Figure 2-26). Two straight 1.3-mm wires were inserted, across

the width (medial-lateral direction) of the patella, one proximal and one distal. These holes were then over drilled using a 2.7mm cannulated drill bit. Using a fine saw blade 0.1mm thick, the patella was split from proximal to distal along its length, 10mm lateral to the midline (see Figure 2-25 and Figure 2-27). The split was performed under a sufficient amount of quadriceps tension, to stabilise the patella, with the knee at 90° flexion. An osteotome was used to widen the gap between the two fragments superficial to the articular surface, which was finally incised with a scalpel. This final cut was extended 10mm proximally and distally through and parallel to the quadriceps tendon and patellar tendon fibres, respectively. The two fragments were then approximated with two 4.0mm partially threaded cannulated cancellous screws (see Figure 2-28).

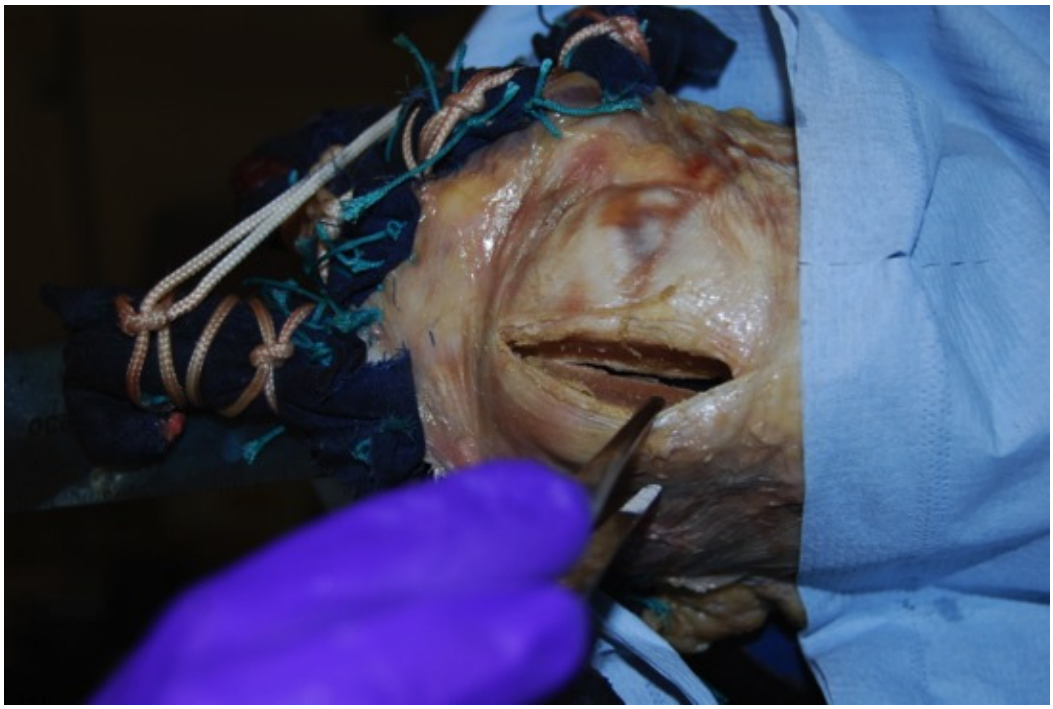


Figure 2-25 Transpatellar approach - patellar splitting

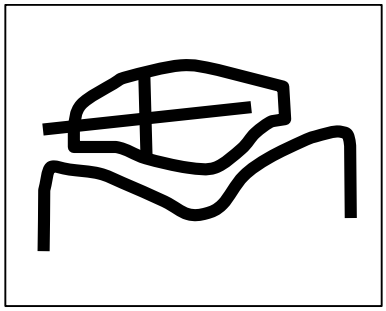


Figure 2-26 Parallel proximal and distal holes for accurate screw fixation

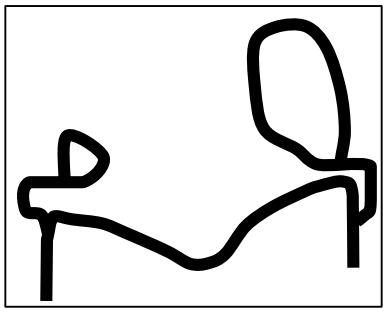


Figure 2-27 Splitting of the patella off-centre after screw holes drilled

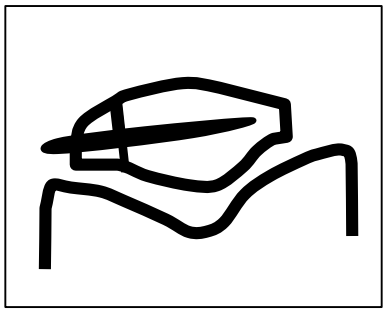


Figure 2-28 Approximation of the two fragments with cannulated cancellous screws

This approach was performed prior to the native knee condition experiments to minimise variability between the four conditions. Prior work had shown that this approach did not alter the patellar tracking or retinacula significantly (Merican *et al.*, 2009). Care was taken to ensure the patella remained intact and the screw fixation did not interfere with subsequent implantation of the patellar button for the other three conditions. The patellar button was cemented in with ease; no obstruction

was caused by the transpatellar approach and screw fixation (see Figure 2-22). The screws were positioned superficial enough, both proximally and distally, allowing for an adequate patellar resection to be performed. The split in the quadriceps tendon was opposed with a continuous stitch, which was released to ease prosthesis implantation. The patellar tendon split was not repaired, as loading the knee during flexion does not cause separation of the tendon.

All three types of knee arthroplasty were performed on each knee specimen in accordance with the manufacturer's guidelines (Zimmer, Warsaw, Indiana, USA). The same surgeon, a knee arthroplasty orthopaedic consultant, implanted all the prostheses.

Four cycles were carried out per condition. The order of experiments was native, PFA, CR-TKA and PS-TKA. Between each arthroplasty condition, the cement was excised and reapplied for the components that required exchanging. The same patellar button was used for all three arthroplasty conditions. The same tibial tray was used for the CR-TKA and PS-TKA. It was not possible to randomise the order of tests, in view of the progressive bone removal.

2.14.5 Measurement: Extensor Mechanism Efficiency

In order to measure this primary outcome two preliminary experiments were performed:

Experiment 1. Strain gauge calibration

Experiment 2. Attachment and testing of strain gauge

Experiment 1: Strain Gauge Calibration

The strain gauge elements were configured in a full bridge strain gauge circuit (Wheatstone Bridge) arrangement whereby two strain gauge elements were bonded to either side of the bar so that those on the superior surface detected compression changes and those on the inferior side detected tensile changes. The schematic view of this configuration is illustrated in Figure 2-29 (Kuphaldt, 2006).

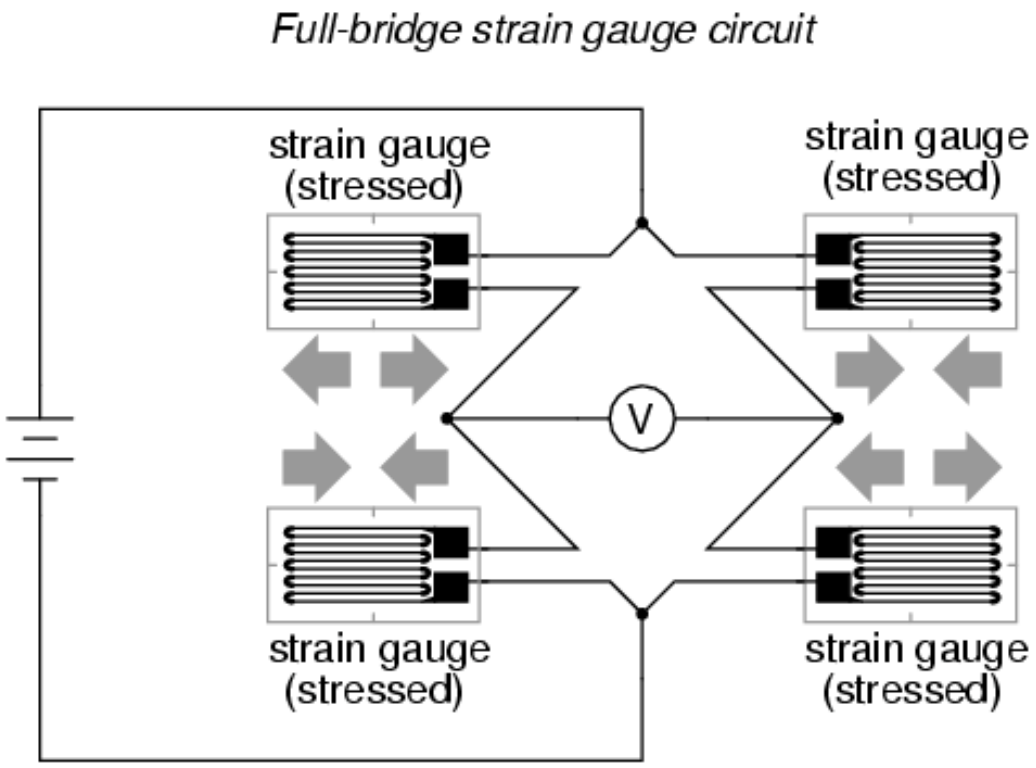


Figure 2-29 Full bridge strain gauge circuit

(Kuphaldt, 2006)

Each strain gauge was active in the configuration. The function of each strain gauge is illustrated in Figure 2-30 (Kuphaldt, 2006).

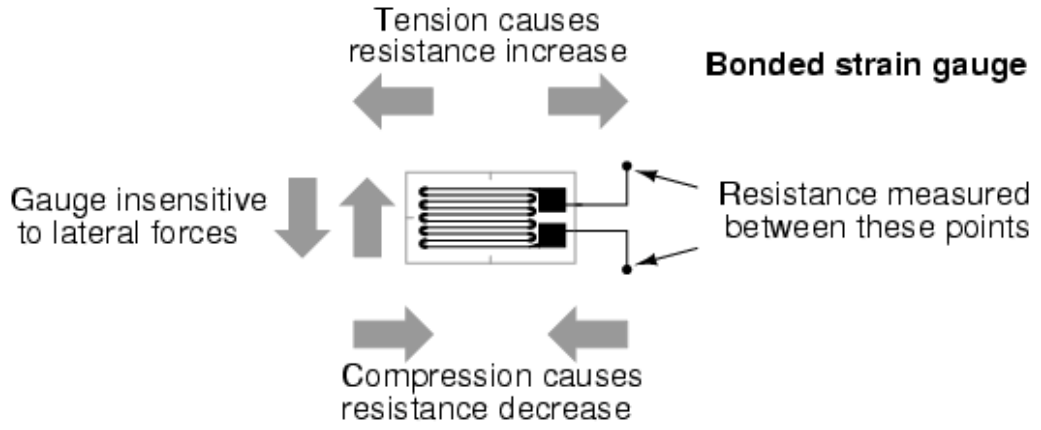


Figure 2-30 Single strain gauge

(Kuphaldt, 2006)

Silicone sealant was used to protect the strain gauge elements and minimise the effect of external factors such as changes in temperature and humidity Figure 2-31. The strain gauge was connected to a strain gauge amplifier system, Sangamo Schlumberger type C56 (Sangamo Company, Bogner Regis, UK) which converted the strain gauge input (mV) into mA readings Figure 2-32.

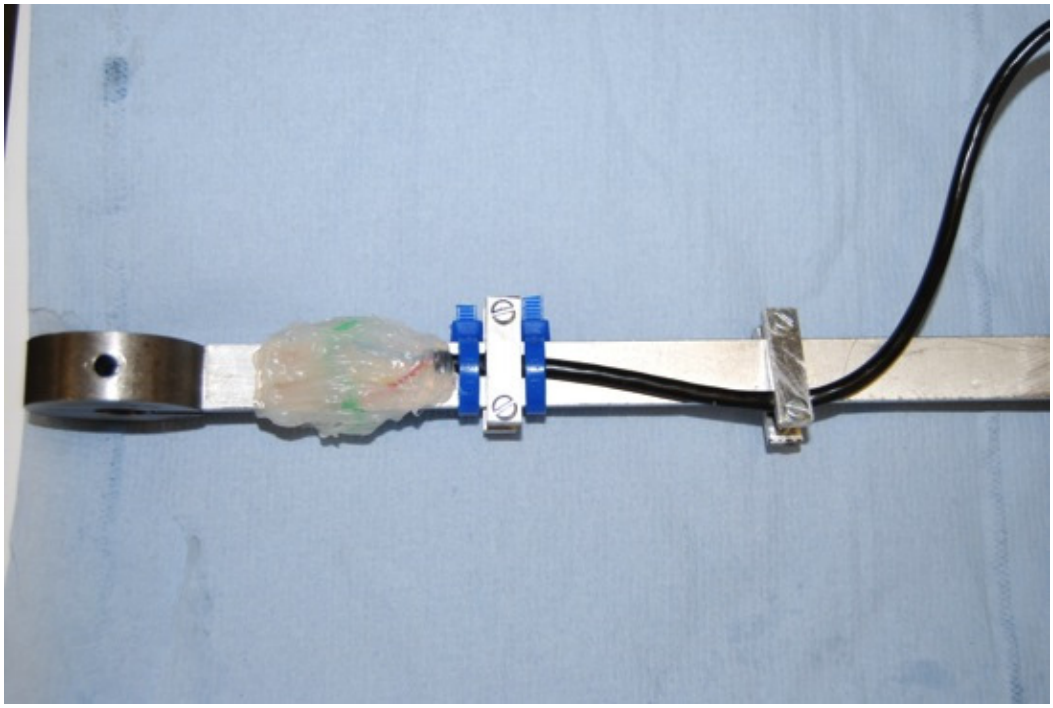


Figure 2-31 Bonded strain gauges and silicone sealant

Figure 2-32 Strain gauge amplifier system

The strain gauged beam was held in a clamp parallel to the ground. The clamp was 90cm above ground level, allowing for adequate clearance of the weights applied to the strain gauge. The distance from the strain gauge elements to the point of weight application, moment arm, measured 25cm. The weights, force, were applied in increments of 5N up to 50N, therefore 10 data points were collected. The torque or moment at each 5N increment was calculated. Four sensitivity levels were assessed: 1, 2.5, 10 and 25, to determine the setting that produced the least variability in mA readings with increase in Newtons. Four trials were performed at each sensitivity level and an average was taken of the four trials. The average values were multiplied by the moment and the trend assessed (see Table 2-10 and Figure 2-33).

Table 2-10 Strain gauge calibration

Sensitivity Level	Trial	Moment (Nm)									
		1.25	**2.5**	**3.75**	**5**	**6.25**	**7.5**	**8.75**	**10**	**11.25**	**12.5**
1	**1**	82	166/7	241/2	308/9	390/1	469/8	527	597/8	674/5	765/6
	2	81	156	243	334	384/5	474/5	538/9	632/3	701/2	808/9
	3	81	152	227/8	303	391/2	470/1	551/2	626/7	679/80	752/3
	4	79	166/7	249/50	327/8	398	463/4	527/8	597/8	675	849/50
	Mean	81	160	240	318	391	470	536	614	683	794
	MF	0.015479876	0.015600624	0.015600624	0.015710919	0.015979546	0.015974441	0.016320821	0.016299919	0.016480498	0.015743073
	Mean MF	0.015919034									
2.5	**1**	32	61	91	122	150	180	211	240	270	301
	2	32	64	97	129	158	188	211	243	273	301
	3	32	64	95	127	157	188	220	250	281	313
	4	32	64	97	129	158/9	191	221/2	249/50	281	317
	Mean	32	61	91	122	150	180	211	240	270	301
	MF	0.0390625	0.040983607	0.041208791	0.040983607	0.041666667	0.041666667	0.041469194	0.041666667	0.041666667	0.041528239
	Mean MF	0.04119026									
10	**1**	8	16	24	32	39/40	48	55	63	71	79/80
	2	8	16	24	32/3	40	48	56	64	72	80
	3	8	16	24	32	40	48	56	63	71	79
	4	8	16	24	33	40	48	56	64	72	80
	Mean	8	16	24	33	40	48	56	64	72	80
	MF	0.15625	0.15625	0.15625	0.151515152	0.15625	0.15625	0.15625	0.15625	0.15625	0.15625
	Mean MF	**0.155776515**									
25	**1**	3	7	10	13	16	19	22	25	28	32
	2	3	7	10	13	16	19	22	25	29	32
	3	3	7	10	13	16	19	22	25	28	31/2
	4	3	7	10	13	16	19	22	25	29	32
	Mean	3	7	10	13	16	19	22	25	28	32
	MF	0.416666667	0.357142857	0.375	0.384615385	0.390625	0.394736842	0.397727273	0.4	0.401785714	0.390625
	Mean MF	0.390892474									

This table shows the output readings at increasing moments for four different sensitvity settings on the amplifier system. Each setting was tested four times at each moment and an average value was calculated. The Multiplication Factor (MF) was calculated by dividing the moment value by the mean output reading.

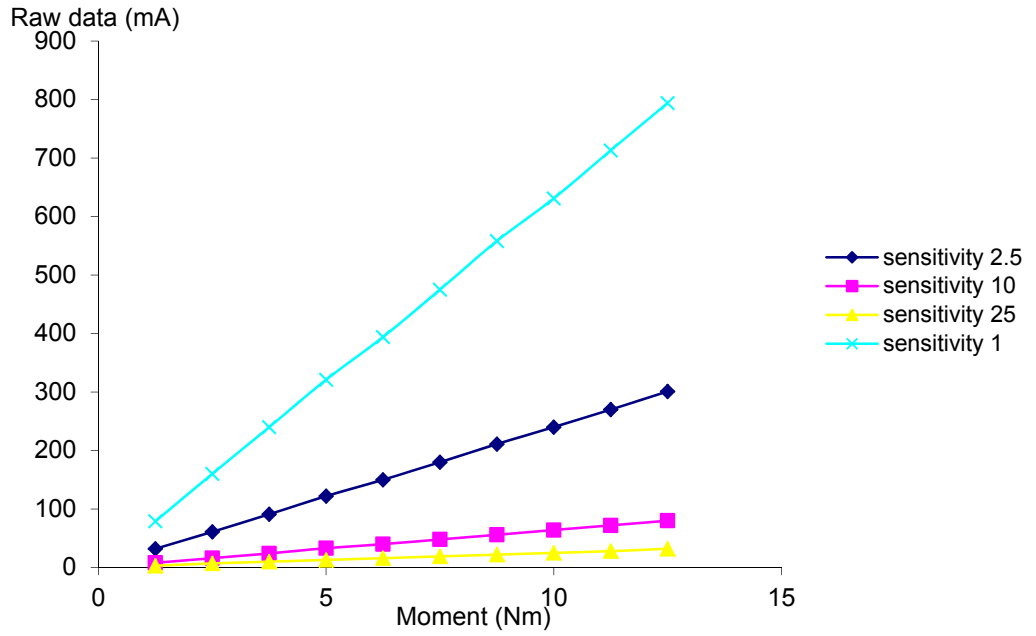


Figure 2-33 Calibration plot

This calibration plot illustrates the output reading for each sensitivity level tested at moments ranging from 1.25 to 12.5Nm, at increments of 1.25Nm. Sensitivity levels 10 and 25 produced low output readings below 100 for the entire range, demonstrating low risk of producing values beyond the measuring capacity of the amplifier system. In contrast, sensitivity levels 1 and 2.5 demonstrated higher gradients and thus a high risk of exceeding the maximum output reading of the amplifier system.

Figure 2-33 demonstrates the linear relationship between increase in moment and change in mA readings generated by the amplifier (transducer). Sensitivity setting 1 had such a high gradient that it is likely higher moments (due to increased force) would have produced readings exceeding the maximum reading output of the amplifier system. In addition, the variability in multiplication factor (MF) (see Table 2-10) was greater than in comparison to the other settings. Sensitivity setting 2.5 was also not appropriate to use, although the gradient was not as high, the variability in multiplication factor would lead to unreliable data. Therefore the choice remained between settings 10 and 25, both of which had very low gradients and were unlikely to result in readings exceeding

those that could be outputted by the transducer. Sensitivity level 10 produced the most consistent multiplication factor and was therefore the setting of choice. This moment multiplication factor (0.1558) was converted to ‘force’ multiplication factor (0.6231) in order to calculate the extensor mechanism efficiency.

Experiment 2. Attachment and Testing of the Strain Gauged Beam

Two metal discs were joined to each end of the strain gauged aluminium bar using adhesive. Each disc had a central hole to aid mounting and securing of the device to the outer right side of the rig as shown in Figure 2-34. The disc nearest to the strain gauge elements was connected to the crank mechanism. This connection was reinforced with a thin strip of stainless steel to reduce the amount of play (potential additional torque) in the system that could have impacted on the results. A metal shaft was inserted in the central hole of the disc furthest from the strain gauge elements and was used to position the strain gauge and crank mechanism at the appropriate flexion angle. The position of the strain gauge device in relation to the crank mechanism was checked at each angle to ensure it remained parallel. An additional counter balance was placed on the outer left side of the rig to ensure this position was maintained.

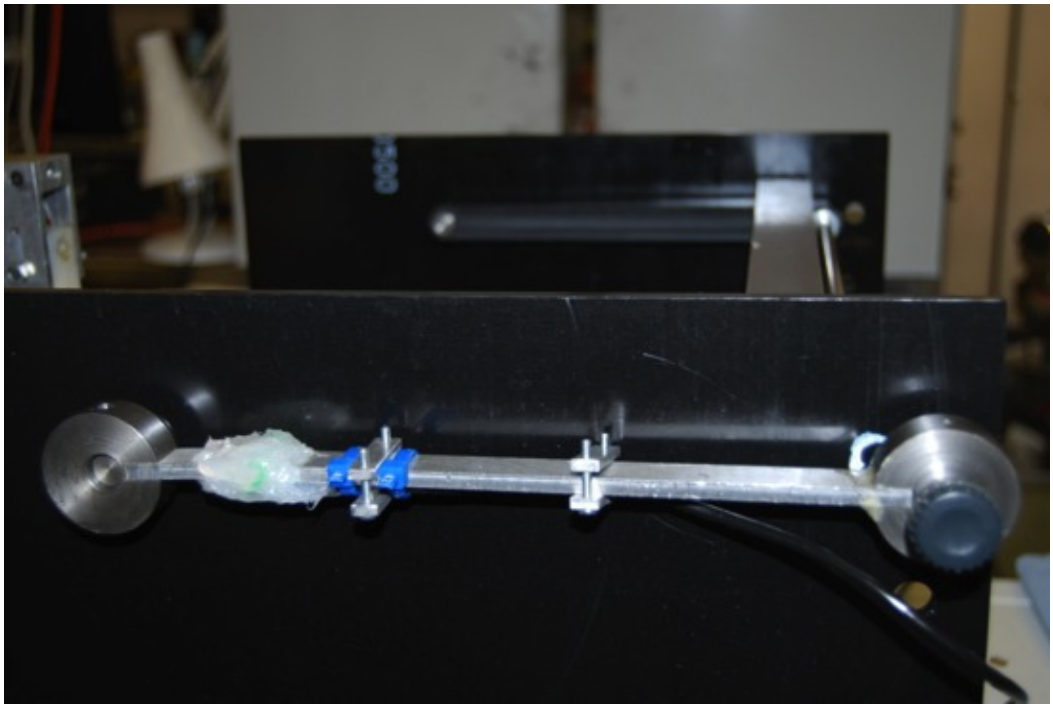


Figure 2-34 Strain gauge device attached to outer aspect of rig

The calibrated strain gauge was tested on the rig (without a knee) to ensure the level of consistency found in Experiment 1 was reproducible. The tests were repeated at two time points during the day to assess for significant variations in readings as a result of unknown and known external factors such as humidity and temperature (see Table 2-11 and Figure 2-35).

Table 2-11 Calibration Assessment on Rig

Angle	Morning Trials		Afternoon Trials	
	Trial 1: 0° to 120°	Trial 2: 120° to 0°	Trial 3: 0° to 120°	Trial 4: 0° to 120°
0°	-22	-22	-21	-21
10°	-21	-21	-20	-21
20°	-20	-20	-20	-20
30°	-19	-20	-19	-19
40°	-19	-18	-18	-19
50°	-18	-17	-17	-17
60°	-17	-16	-15	-16
70°	-15	-15	-15	-14
80°	-14	-15	-13	-14
90°	-13	-13	-13	-14
100°	-13	-13	-12	-13
110°	-10	-11	-10	-10
120°	-8	-8	-8	-8

This table shows the results of the unloaded strain gauge at each flexion angle for four trials: two tests in the morning and two tests in the afternoon.

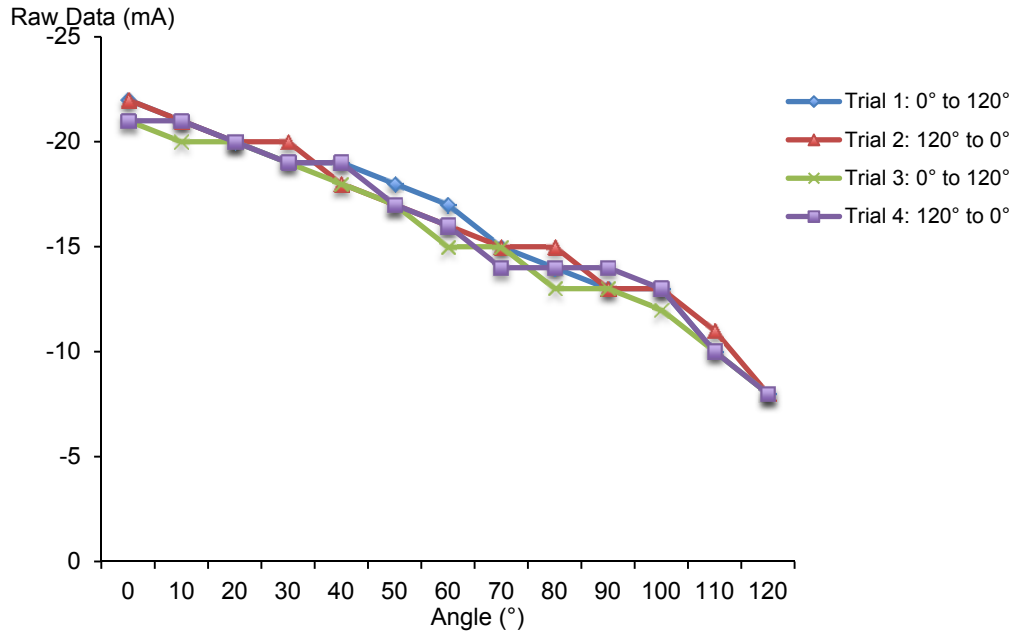


Figure 2-35 Calibration on Rig Plot

This calibration plot demonstrates all four trials produce similar values at each flexion angle.

Statistical analysis for significant variation between the trials yielded two positive results. The level of significance was set at $p = 0.00833$ using the Bonferroni adjustment to reduce the risk of a Type I error (see Table 2-12). Significant differences occurred between morning and afternoon results but this was not consistent for both morning and afternoon trials. The detected difference may have been related to changes in temperature and humidity. No significant difference occurred between the two trials in the morning or between the two trials performed in the afternoon. Furthermore, the intraclass correlation coefficient was calculated as 0.996, demonstrating excellent intraclass reliability (consistency of the output data, thus indicating the number of trials (four) is sufficient.

Table 2-12 Statistical Assessment for Variation

Time	Comparison	P value
Morning (m)	Trial 1m vs Trial 2m	1
Afternoon (a)	Trial 1a vs Trial 2a	0.054360123
Morning vs Afternoon	Trial 1m vs Trial 1a	0.005161681
Morning vs Afternoon	Trial 1m vs Trial 2a	0.190151431
Morning vs Afternoon	Trial 2m vs Trial 1a	0.005161681
Morning vs Afternoon	Trial 2m vs Trial 2a	0.273483563

Calibration on the rig without a knee demonstrated at each angle of flexion some degree of strain was detected. In order to 'zero' the raw data obtained with the knees *in situ*, measurements were taken before each condition was tested without the knees. These figures were subtracted

from the raw data and the corrected mean was used to calculate the extensor mechanism efficiency.

Following completion of calibration, each knee was mounted in the rig under constant quadriceps tension (205N), the extension force generated, at each measured angle of knee flexion, was applied to the aluminium bar (see label C in Figure 2-9) perpendicular to the tibial shaft. This force was detected by the strain gauges. This was repeated four times per condition for each knee tested.

2.15 Interventions

2.15.1 Patellofemoral Arthroplasty

The Zimmer® Gender Solutions™ Patello-Femoral Joint System (Zimmer, Warsaw, Indiana, USA) trochlear component is an asymmetrical onlay component made from forged cobalt chrome. The femoral trochlear groove is wide and the lateral facet prominent to ensure engagement of the patella in the first 30° of knee flexion (see Figure 2-36). The anterior flange is relatively long allowing for the patellar button to maintain contact in full extension and low profile to avoid overstuffing. The intercondylar segment of the prosthesis is tapered towards the notch to ensure a smooth transition from prosthesis to native femoral condyle in deep knee flexion. The under-surface of the trochlear component has three pegs, which are configured to maximise secure cement hold of the component

during knee motion (see Section 2.2.3.1). The patellar button made from ultra-high molecular weight polyethylene (UHMWPE) is axisymmetric and also has pegs on the under surface to add stability and fixation. Both articulating areas are resected using jigs and clamps respectively. The trochlear implant and patellar button are both cemented in place. The native tibiofemoral joint and cruciate ligaments remain *in situ*. The trochlear prosthesis is available in five sizes. Sizes 1-4 have the same patellar contact geometry as the NexGen CR-TKA and PS-TKA used in this study and therefore were the only sizes selected, following confirmation with the product engineer designers.

Figure 2-36 Patello-Femoral Joint System, Zimmer

2.15.2 Total Knee Arthroplasty

The Cruciate retaining total knee arthroplasty (CR-TKA): Zimmer NexGen CR-Flex System (Zimmer, Warsaw, Indiana, USA) and Posterior-stabilising total knee arthroplasty (PS-TKA): Zimmer NexGen LPS-Flex System (Zimmer, Warsaw, Indiana, USA) were used in the study. Both femoral components were made of cobalt chromium

molybdenum alloy and have been designed with minimised width and thickness of the anterior flange to relieve tension on the extensor mechanism and restore normal joint function. The intercondylar geometry of both components is identical to that of the Zimmer PFA. These components are asymmetrical and multi-radius. The trochlear groove is deepened to accommodate the axisymmetric patellar button and reduce the risk of overstuffing.

The cruciate retaining femoral component is shown in Figure 2-37. The space between the posterior condyles accommodates the native posterior cruciate ligament. The tibial polyethylene insert is highly congruent and fixed to the tibial base plate. The tibial cut created a 7° posterior slope. The same base plate was used for the PS-TKA.

The posterior stabilising femoral component, shown in, Figure 2-37 has an additional horizontal metal construct between the two posterior condyles. This articulates with the polyethylene tibial post, forming a post-cam mechanism. All the metal implants were cemented to bone with poly methyl methacrylate (PMMA).

Figure 2-37 Posterior-stabilising TKA, Zimmer (left), Cruciate-retaining TKA, Zimmer (right)

2.16 Adverse Events Management

Each cadaver was used for the purpose of this study alone. All tissue handling was carried out in accordance with the Tissue Handling Guidelines and The Biomechanics Laboratory manual for 'working practices relating to biological safety'. Both documents instructed on collection, use, storage and disposal of biological tissue. Any deviation from these guidelines was considered an adverse event. All reportable incidences, such as contamination of a lab worker with human material, followed the incident event protocol. This involved first aid attention and the departmental safety officer and head of the lab being informed.

2.17 End of Study

The study was deemed complete when all 8 cadaveric knees had a set of four clean results.

2.18 Data Management

2.18.1 Statistical Analysis

A sample size calculation, based on previous cadaveric knee biomechanics test data, established 8 knees were sufficient for detecting change of meaningful significance with 95% confidence at 80% power (Stephen *et al.*, 2013). Other studies have also performed power calculations supporting this sample size (Cohen *et al.*, 2001; Stephen *et al.*, 2012). The kinematic data was analysed using a one-way repeated measures ANOVA. The single factor evaluated was the knee condition: native, PFA, CR-TKA, PS-TKA at each 10° increment of knee flexion. The

dependent variables were the primary outcome: extensor mechanism efficiency and secondary outcomes: patellofemoral resultant force, peak pressure and contact area (dependent variables). When the F test was significant ($P < 0.05$) the null hypothesis was rejected. Thus confirming the existence of differences between the conditions, that is, (the samples are not all from populations with the same mean) the means for the dependent variables measured at a given angle for the four conditions were not from the same populations. Post hoc paired *t* tests were used to identify which condition differed from the others at each angle of flexion for each dependent variable.

Comparing four conditions means a multiple of six paired comparisons will be made at a given angle of flexion. This method of performing multiple hypotheses tests results in an increased probability that one or more of the test will be significant due to chance (Type I error). The likelihood of these occurring increases as the number of comparisons increases. This occurrence is known as the familywise error rate (FWER) (another description: familywise type 1 error is the probability that, even if all samples come from the same population, one will wrongly conclude that at least one pair of populations differ) or cumulative Type I error/alpha inflation and is estimated with the following formula:

$$\alpha_{FWE} \leq 1-(1-\alpha_{EC})^{c}$$

where α_{FWE} is the FWER, α_{EC} is the desired significance level, and ^{c} the number of comparisons. In this study the calculated FWER is ≤ 0.2649, that is, 1 in 4 significant tests will be due to a Type I error. This rate is unacceptable and therefore a multiplicity adjustment is required.

The Bonferroni factor was used to calculate an adjusted probability. This method of adjustment is very conservative and guarantees that the use of the adjusted alpha in pairwise comparisons keeps the actual probability of FWER no higher than the desired significance level, that is, 0.05. The formula is as follows:

$$\alpha_B = \frac{\alpha_{FWE}}{c}$$

where α_B is the new alpha used to evaluate each comparison and α_{FWE} is the maximum allowed FWER. The total number of pairs *c* = 4(4-1)/2 = 6, therefore the α_B significance level is 0.00833 for comparison of the four knee conditions to each other.

All data analysis was performed in IBM® SPSS® Statistics for Macintosh, Version 19.0 (Armonk, NY: IBM® Corp.) and Microsoft® Excel® Version 14.3.9 (Microsoft® Corp.).

2.19 Results

Eight knees were analysed in total. The raw data collected for each knee had to undergo a series of computations, which varied depending on the outcome being assessed, prior to performing statistical analysis. Summary data for each parameter are recorded in Appendices I to V: Table 6-1 to Table 6-39.

2.19.1 Extensor Mechanism Efficiency

Each knee underwent a sequence of sixteen trials. Four trials were performed under each condition: native knee, PFA, CR-TKA and PS-TKA. The raw data was converted into extensor mechanism efficiency (EME).

Extensor mechanism efficiency results are summarised in Table 2-13 to Table 2-16. The data shows all four conditions demonstrate a similar pattern of increasing EME between 0° and 50°, highest in mid-range, and a decreasing EME between 60° and 120°, lowest in mid-range. This is clearly illustrated in Figure 2-38.

Table 2-13 Native Knee Extensor Mechanism Efficiency

Flexion Angle (°)	Mean Native Knee Nm/N_{QT}	Standard Deviation (±SD)
120	0.11097	0.02299
110	0.07843	0.01203
100	0.07285	0.00995
90	0.07421	0.00763
80	0.07858	0.00544
70	0.08613	0.00621
60	0.09874	0.00406
50	0.11177	0.00478
40	0.12277	0.00874
30	0.13317	0.01186
20	0.13849	0.01239
10	0.12475	0.01545
0	0.04880	0.02150

Table 2-14 PFA Extensor Mechanism Efficiency

Flexion Angle (°)	Mean PFA Knee Nm/N_{QT}	Standard Deviation (±SD)
120	0.10919	0.01344
110	0.07350	0.01127
100	0.06744	0.01061
90	0.06670	0.01406
80	0.06601	0.01408
70	0.07839	0.01750
60	0.09339	0.02555
50	0.11978	0.02269
40	0.13749	0.01655
30	0.14452	0.01204
20	0.14471	0.01717
10	0.12222	0.02282
0	0.05399	0.04269

Table 2-15 CR-TKA Extensor Mechanism Efficiency

Flexion Angle (°)	Mean CR-TKA Knee Nm/N_{QT}	Standard Deviation (±SD)
120	0.11166	0.02178
110	0.08024	0.01780
100	0.07366	0.01508
90	0.07487	0.01391
80	0.07577	0.01243
70	0.08271	0.01366
60	0.09214	0.01661
50	0.09928	0.01758
40	0.10852	0.01526
30	0.11128	0.01519
20	0.10814	0.01707
10	0.07927	0.02061
0	0.01639	0.01793

Table 2-16 PS-TKA Extensor Mechanism Efficiency

Flexion Angle (°)	Mean PS-TKA Knee Nm/N_{QT}	Standard Deviation (±SD)
120	0.10774	0.01673
110	0.08276	0.01528
100	0.07672	0.01534
90	0.07592	0.01301
80	0.07423	0.00948
70	0.07846	0.00881
60	0.08679	0.01271
50	0.09318	0.01534
40	0.10235	0.01824
30	0.11180	0.01428
20	0.11218	0.01391
10	0.07981	0.02600
0	0.01249	0.01523

One-way ANOVA analysis at each 10° increment of flexion showed no significant difference at 60°, 70°, 90° to 120° of knee flexion between any of the four conditions. The positive findings are listed in Table 2-17. The main significant differences occurred at lower degrees of knee flexion (0° to 50°). Throughout this range of motion, the PFA showed the greatest extensor mechanism efficiency and was found to be significantly different to the CR- and PS-TKA. Interestingly, the converse was true in the deep knee flexion range, although the differences were not statistically significant. There were no differences between the CR-TKA and PS-TKA at any of the measured points of knee flexion. The significant differences between the native and the arthroplasty conditions were similar to the PFA. The distribution appeared bimodal.

Table 2-17 Extensor Mechanism Efficiency Significant Differences

Angle	Condition (I)	Condition (J)	Mean difference (I-J)	Std. Error	Sig.	99.166667% Confidence Interval	
						Lower Bound	Upper Bound
80°	Native	PFA	0.1256	0.00265	0.000	0.0039	0.0212
80°	PFA	CRTKA	-0.00976	0.00265	0.002	-0.0184	-0.0011
50°	Native	PSTKA	0.1859	0.00399	0.000	0.0055	0.0317
50°	PFA	CRTKA	0.02049	0.00399	0.000	0.0074	0.0336
50°	PFA	PSTKA	0.02660	0.00399	0.000	0.0135	0.0397
40°	Native	PFA	-0.01472	0.00396	0.002	-0.0277	-0.0018
40°	Native	CRTKA	0.01425	0.00396	0.003	0.0013	0.0272
40°	Native	PSTKA	0.02042	0.00396	0.000	0.0075	0.0334
40°	PFA	CRTKA	0.02897	0.00396	0.000	0.0160	0.0419
40°	PFA	PSTKA	0.03514	0.00396	0.000	0.0222	0.0481
30°	Native	PFA	-0.01135	0.00345	0.008	-0.0226	-0.0001
30°	Native	CRTKA	0.02189	0.00345	0.000	0.0106	0.0332
30°	Native	PSTKA	0.02137	0.00345	0.000	0.0101	0.0327
30°	PFA	CRTKA	0.03324	0.00345	0.000	0.0220	0.0445
30°	PFA	PSTKA	0.03272	0.00345	0.000	0.0214	0.0440
20°	Native	CRTKA	0.03035	0.00383	0.000	0.0178	0.0429
20°	Native	PSTKA	0.02631	0.00383	0.000	0.0138	0.0389
20°	PFA	CRTKA	0.03657	0.00383	0.000	0.0240	0.0491
20°	PFA	PSTKA	0.03253	0.00383	0.000	0.0200	0.0451
10°	Native	CRTKA	0.04545	0.00521	0.000	0.0284	0.0625
10°	Native	PSTKA	0.04490	0.00521	0.000	0.0279	0.0619
10°	PFA	CRTKA	0.04296	0.00521	0.000	0.0259	0.0600
10°	PFA	PSTKA	0.04241	0.00521	0.000	0.0254	0.0594
0°	Native	CRTKA	0.03241	0.00636	0.000	0.0116	0.0532
0°	Native	PSTKA	0.03631	0.00636	0.000	0.0155	0.0571
0°	PFA	CRTKA	0.03761	0.00636	0.000	0.0168	0.0584
0°	PFA	PSTKA	0.04151	0.00636	0.000	0.0207	0.0623

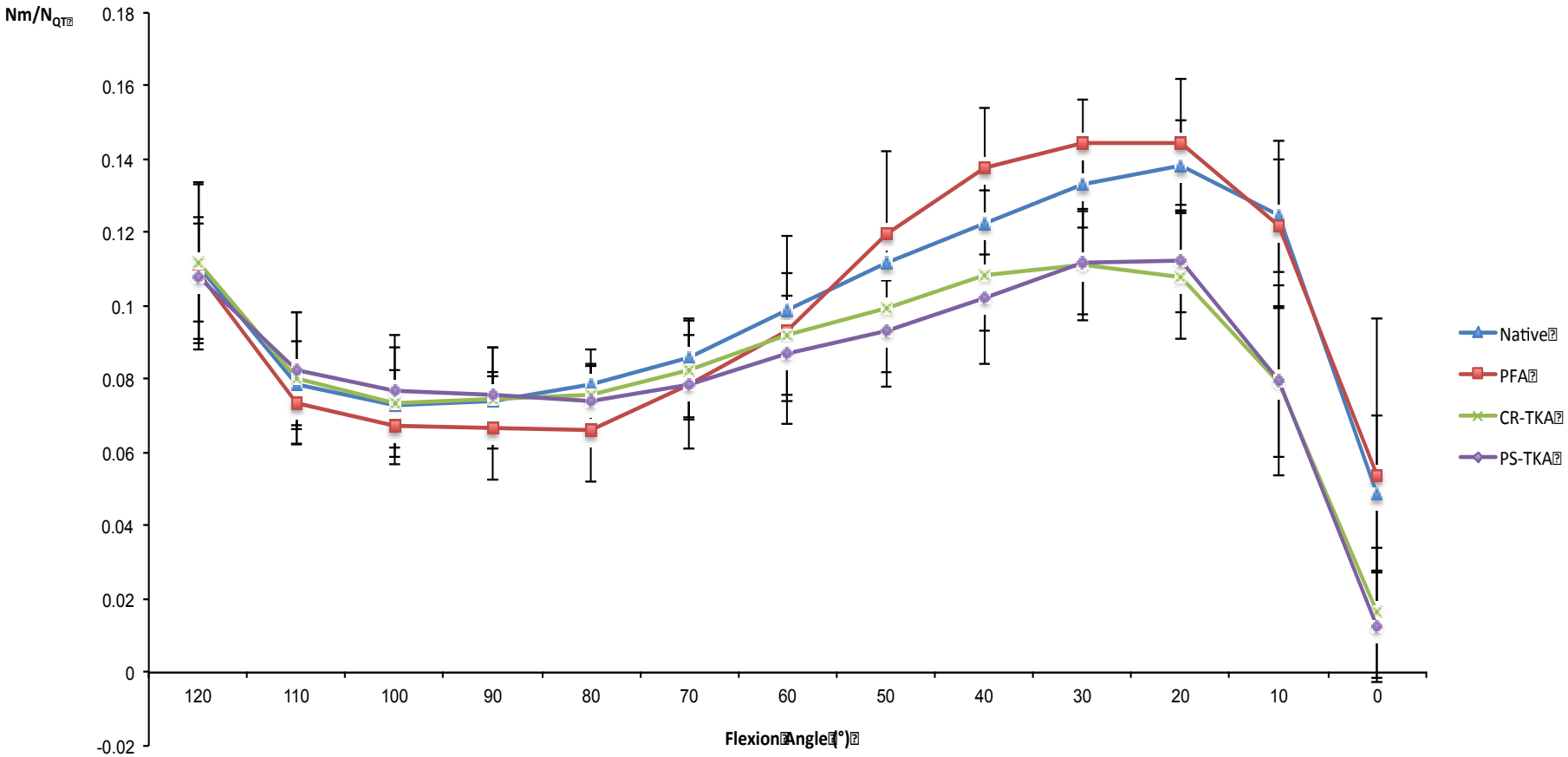


Figure 2-38 Extensor Mechanism Efficiency

The extensor mechanism efficiency (EME) graph illustrates the change in EME during the flexion-extension cycle for all four conditions. There is an increased efficiency from mid- to early knee flexion demonstrated by all conditions. Interestingly, the PFA condition appears to produce higher EME than the native knee during this range of motion.

2.19.2 Patellofemoral Resultant Forces

The resultant force was assessed at five angles: 0°, 30°, 60° 90° and 120°. Two trials were performed at each angle of knee flexion. The resultant force was generally higher for both the native knee and PFA than CR-TKA and PS-TKA at each angle of knee flexion assessed. The results are summarised in Table 2-18 to Table 2-21 and illustrated in Figure 2-39.

Table 2-18 Native Knee Resultant Force

Flexion angle (°)	Mean Native Knee Resultant Force (N)	Standard Deviation (±SD)
120	83.38981	28.14018
90	92.12675	30.56885
60	91.10694	21.27003
30	68.64461	9.65437
0	36.27739	4.44379

Table 2-19 PFA Resultant Force

Flexion angle (°)	Mean PFA Resultant Force (N)	Standard Deviation (±SD)
120	97.27299	30.78750
90	101.91813	29.26406
60	71.39603	16.47219
30	54.66419	12.67899
0	30.08964	9.98869

Table 2-20 CR-TKA Resultant Force

Flexion angle (°)	Mean CR-TKA Resultant Force (N)	Standard Deviation (±SD)
120	83.20236	24.47742
90	82.95448	15.21989
60	82.23976	13.62166
30	51.09061	8.23142
0	22.86889	4.03475

Table 2-21 PS-TKA Resultant Force

Flexion angle (°)	Mean PS-TKA Resultant Force (N)	Standard Deviation (±SD)
120	73.35268	12.93741
90	76.23976	14.65527
60	81.64296	12.63351
30	51.06743	5.85306
0	25.47978	4.57338

One way ANOVA analysis showed no evidence of a difference in resultant force generated between the three arthroplasty conditions at any of the five angles of knee flexion assessed: 0°, 30°, 60°, 90° and 120°. The significant differences found occurred in full extension and early flexion, between the native knee and the arthroplasty conditions as shown in Table 2-22.

Table 2-22 Resultant Force Significant Differences

Angle	Condition (I)	Condition (J)	Mean difference (I-J)	Std. Error	Sig.	99.166667% Confidence Interval	
						Lower Bound	Upper Bound
30°	Native	PFA	13.98042	3.81236	0.003	1.1762	26.7847
30°	Native	CRTKA	17.55400	3.81236	0.000	4.7497	30.3583
30°	Native	PSTKA	17.57717	3.81236	0.000	4.7729	30.3814
0°	Native	CRTKA	13.40849	2.42206	0.000	5.2737	21.5433
0°	Native	PSTKA	10.62119	2.42206	0.000	2.4864	18.7560

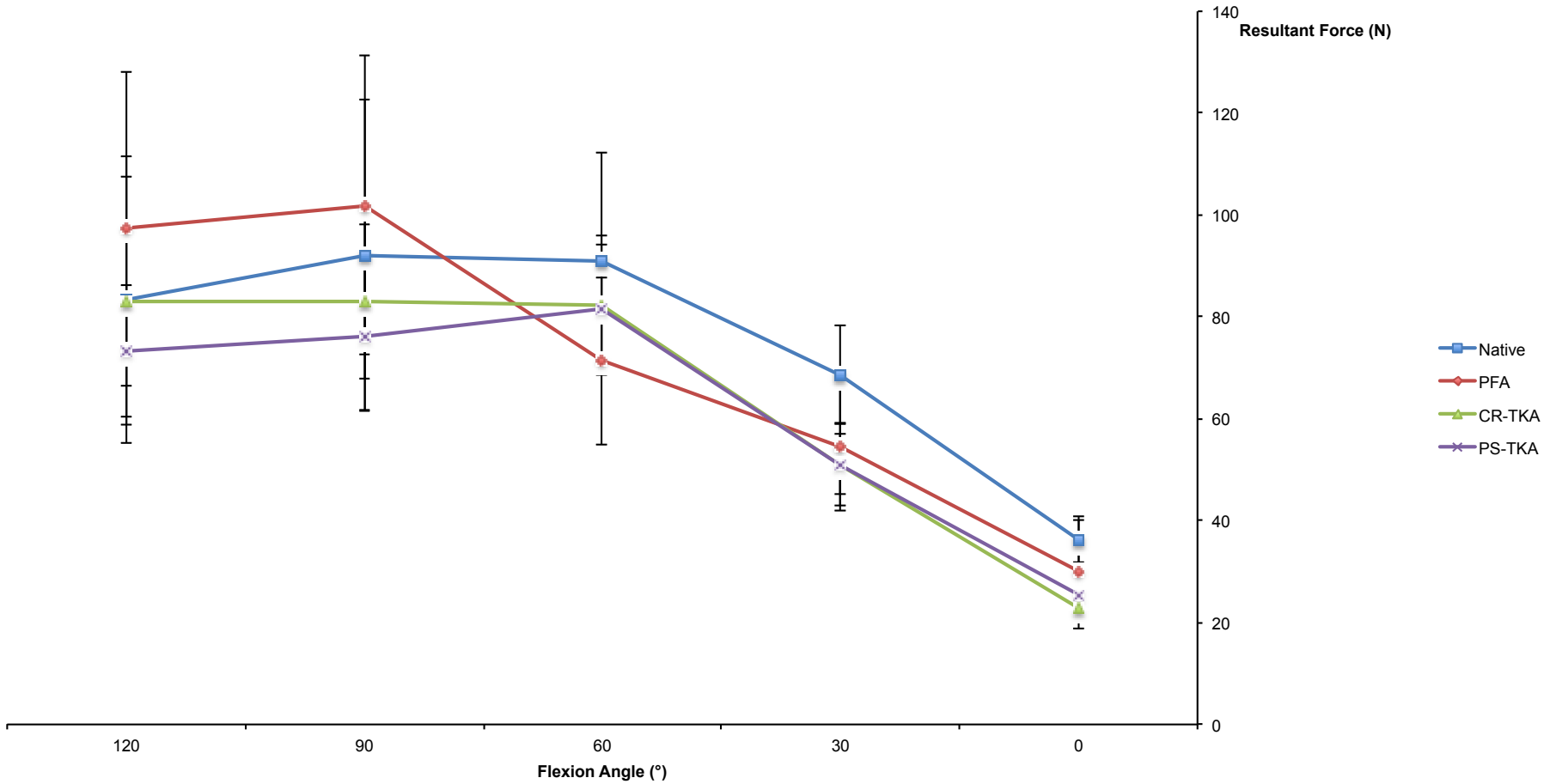


Figure 2-39 Resultant Force

The resultant force graph illustrates the change in force during the flexion-extension cycle for all four conditions. The force generated decreases with decrease in knee flexion angle for all conditions.

2.19.3 Peak Pressures

The peak pressure was assessed at five angles: 0°, 30°, 60° 90° and 120°. Two trials were performed at each angle of knee flexion. The peak pressures were lowest for the native knee condition. All three arthroplasty conditions were comparable at 0°, 30° and 60°. The peak pressure generated by the PFA at 90° and 120° was lower than the CR-TKA and PS-TKA but higher than the native knee. These findings are summarised in Table 2-23 to Table 2-26.

Table 2-23 Native Knee Peak Pressure

Flexion angle (°)	Mean Native Knee Peak Pressure (MPa)	Standard Deviation (±SD)
120	1.73071	1.76180
90	1.43142	0.63990
60	1.18642	0.56963
30	1.19429	0.62976
0	1.65143	0.56323

Table 2-24 PFA Peak Pressure

Flexion angle (°)	Mean PFA Peak Pressure (MPa)	Standard Deviation (±SD)
120	3.05688	0.92771
90	4.43688	1.55034
60	8.25250	0.75889
30	7.83563	0.54030
0	7.13063	1.32606

Table 2-25 CR-TKA Peak Pressure

Flexion angle (°)	Mean CR-TKA Peak Pressure (MPa)	Standard Deviation (±SD)
120	8.10125	1.17239
90	8.02688	1.19806
60	7.56875	1.15427
30	7.25875	0.99843
0	6.69250	0.88663

Table 2-26 PS-TKA Peak Pressure

Flexion angle (°)	Mean PS-TKA Peak Pressure (MPa)	Standard Deviation (±SD)
120	8.24688	0.60251
90	8.05813	1.01778
60	7.52063	0.92186
30	7.00625	0.70840
0	6.90688	1.23878

One-way ANOVA analysis showed statistically significant differences in peak pressure between the native knee and CR-TKA and PS-TKA conditions at all angles assessed. Similarly, the native knee generated significantly lower peak pressures compared with PFA at 0°, 30°, 60° and 90° but no difference was demonstrated at 120°. The PFA condition generated significantly lower peak pressures than the CR-TKA and PS-TKA at 90° and 120°. This sudden decrease at higher angles of knee flexion is illustrated clearly in Figure 2-40. The highest peak pressures were generated at the deepest knee flexion in the native knee, CR-TKA and PS-TKA. In the PFA condition, the highest peak pressure was observed at 60°. Interestingly, all three arthroplasty conditions generated high peak pressures in full extension. No differences in peak pressures were seen between the CR-TKA and PS-TKA conditions at any of the five angles of knee flexion assessed. A summary of the positive findings is listed in Table 2-27.

Table 2-27 Peak Pressure Significant Differences

Angle	Condition (I)	Condition (J)	Mean difference (I-J)	Std. Error	Sig.	99.166667% Confidence Interval	
						Lower Bound	Upper Bound
120°	Native	CRTKA	-6.36662	0.43712	0.000	-7.8374	-4.8958
120°	Native	PSTKA	-6.51616	0.43712	0.000	-7.9646	-5.0677
120°	PFA	CRTKA	-4.96000	0.43712	0.000	-6.4052	-3.5148
120°	PFA	PSTKA	-5.10954	0.43712	0.000	-6.5320	-3.6871
90°	Native	PFA	-3.00545	0.43443	0.000	-4.4645	-1.5463
90°	Native	CRTKA	-6.59545	0.43443	0.000	-8.0545	-5.1363
90°	Native	PSTKA	-6.59982	0.43443	0.000	-8.0589	-5.1407
90°	PFA	CRTKA	-3.59000	0.43443	0.000	-4.9996	-2.1804
90°	PFA	PSTKA	-3.59438	0.43443	0.000	-5.0040	-2.1847
60°	Native	PFA	-7.06607	0.35378	0.000	-8.2543	-5.8779
60°	Native	CRTKA	-6.38232	0.35378	0.000	-7.5705	-5.1941
60°	Native	PSTKA	-6.33420	0.35378	0.000	-7.5224	-5.1460
30°	Native	PFA	-6.64134	0.32909	0.000	-7.7466	-5.5361
30°	Native	CRTKA	-6.06446	0.32909	0.000	-7.1697	-4.9592
30°	Native	PSTKA	-5.81196	0.32909	0.000	-6.9172	-4.7067
0°	Native	PFA	-5.47920	0.43569	0.000	-6.9425	-4.0159
0°	Native	CRTKA	-5.04107	0.43569	0.000	-6.5044	-3.5777
0°	Native	PSTKA	-5.25545	0.43569	0.000	-6.7188	-3.7921

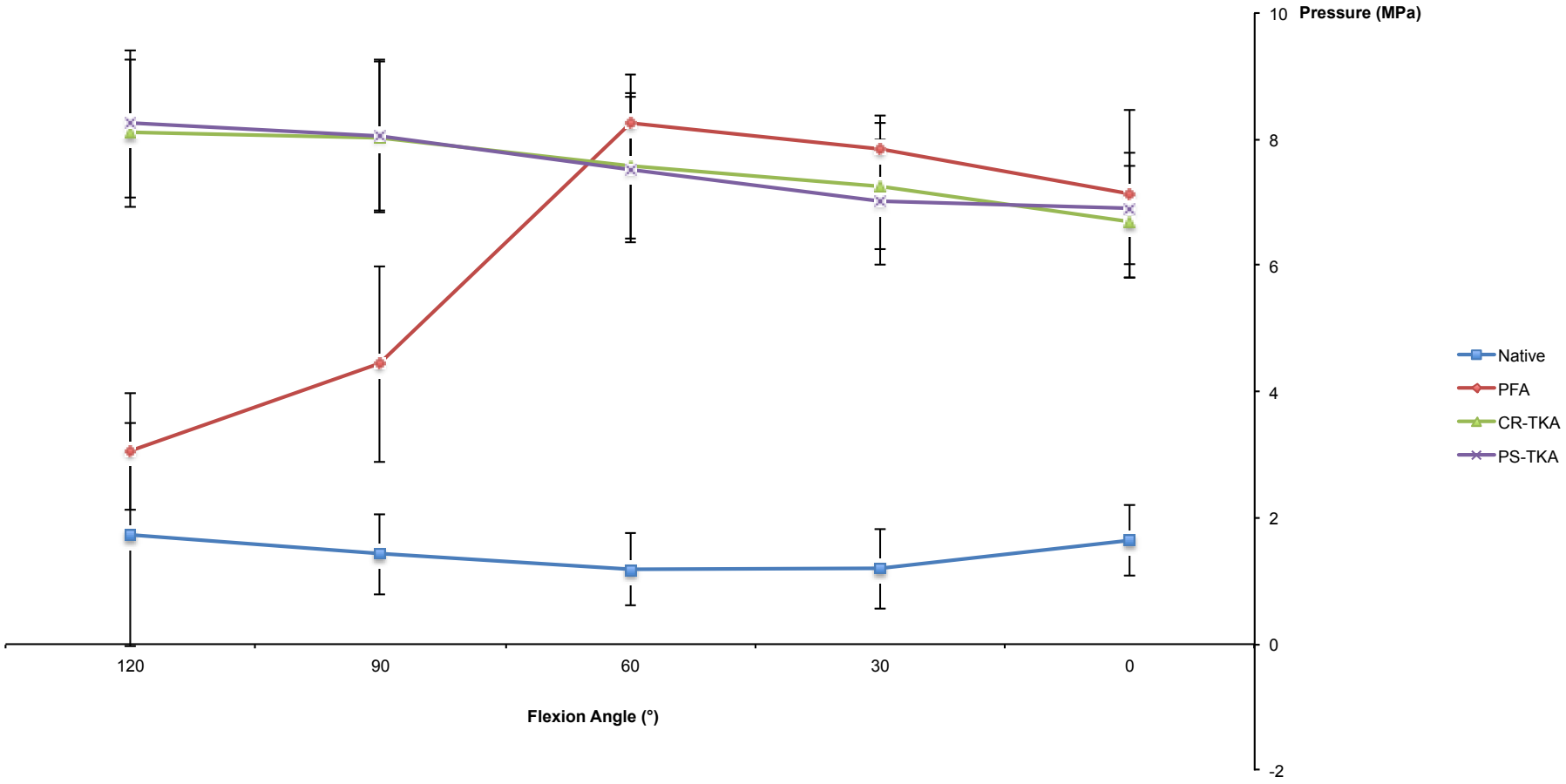


Figure 2-40 Peak Pressure

The peak pressure graph illustrates the consistently low pressure associated with the native knee. The PFA condition demonstrates the point of transition of the patellar component, from articulation with the native femoral condyle to articulation with the trochlear component, as a significant rise in peak pressure at 60° knee flexion.

2.19.4 Contact Areas

The contact area was assessed at five angles: 0°, 30°, 60° 90° and 120°. Two trials were performed at each angle of knee flexion. The contact area was greatest at 60° for the native knee, CR-TKA and PS-TKA. The results of all four conditions are summarised in Table 2-28 to Table 2-31.

Table 2-28 Native Knee Contact Area

Flexion angle (°)	Mean Native Knee Contact Area (mm^2)	Standard Deviation (±SD)
120	288.01786	59.20396
90	308.40952	56.85874
60	338.13296	69.95493
30	229.03180	31.99483
0	117.39608	25.11181

Table 2-29 PFA Contact Area

Flexion angle (°)	Mean PFA Contact Area (mm^2)	Standard Deviation (±SD)
120	108.16511	20.40374
90	106.14898	37.36854
60	44.25389	9.98395
30	38.60879	17.50168
0	19.65722	9.96067

Table 2-30 CR-TKA Contact Area

Flexion angle (°)	Mean CR-TKA Contact Area (mm^2)	Standard Deviation (±SD)
120	32.25800	8.86571
90	36.29025	14.12686
60	47.78211	6.12280
30	30.76607	11.69635
0	13.91124	4.91020

Table 2-31 PS-TKA Contact Area

Flexion angle (°)	Mean PS-TKA Contact Area (mm^2)	Standard Deviation (±SD)
120	28.12492	5.44299
90	32.05633	6.66050
60	44.85878	15.62539
30	17.94351	7.88685
0	13.30643	6.05029

The contact area was significantly higher for the native knee at all angles of knee flexion compared with the three arthroplasty conditions. The contact

area for the PFA condition increased markedly at 90° and 120°, which corresponded with a decrease in peak pressure and significant difference was seen between these values and those recorded for CR-TKA and PS-TKA. The contact areas for both CR-TKA and PS-TKA were consistently low at each angle of knee flexion and no difference was identified between these two conditions.

Table 2-32 Contact Area Significant Differences

Angle	Condition (I)	Condition (J)	Mean difference (I-J)	Std. Error	Sig.	99.166667% Confidence Interval	
						Lower Bound	Upper Bound
120°	Native	PFA	178.7708	12.2037	0.000	137.7093	219.8323
120°	Native	CRTKA	255.2222	12.2037	0.000	214.1607	296.2837
120°	Native	PSTKA	259.8929	12.0182	0.000	219.4556	300.3302
120°	PFA	CRTKA	76.4515	11.9915	0.000	36.1041	116.7988
120°	PFA	PSTKA	81.1222	11.8026	0.000	41.4103	120.8341
90°	Native	PFA	202.2605	13.1175	0.000	158.2038	246.3172
90°	Native	CRTKA	272.1193	13.1175	0.000	228.0626	316.1760
90°	Native	PSTKA	276.3532	13.1175	0.000	232.2965	320.4099
90°	PFA	CRTKA	69.8587	12.6727	0.000	27.2959	112.4215
90°	PFA	PSTKA	74.0927	12.6727	0.000	31.5298	116.6555
60°	Native	CRTKA	290.3509	13.5962	0.000	244.6864	336.0153
60°	Native	PSTKA	293.2742	13.5962	0.000	247.6097	338.9386
30°	Native	PFA	190.4230	8.1145	0.000	163.1696	217.6764
30°	Native	CRTKA	198.2657	8.1145	0.000	171.0123	225.5191
30°	Native	PSTKA	211.0883	8.1145	0.000	183.8349	238.3417
0°	Native	PFA	97.7389	5.2917	0.000	79.9661	115.5117
0°	Native	CRTKA	103.4848	5.2917	0.000	85.7120	121.2576
0°	Native	PSTKA	104.0897	5.2917	0.000	86.3168	121.8625

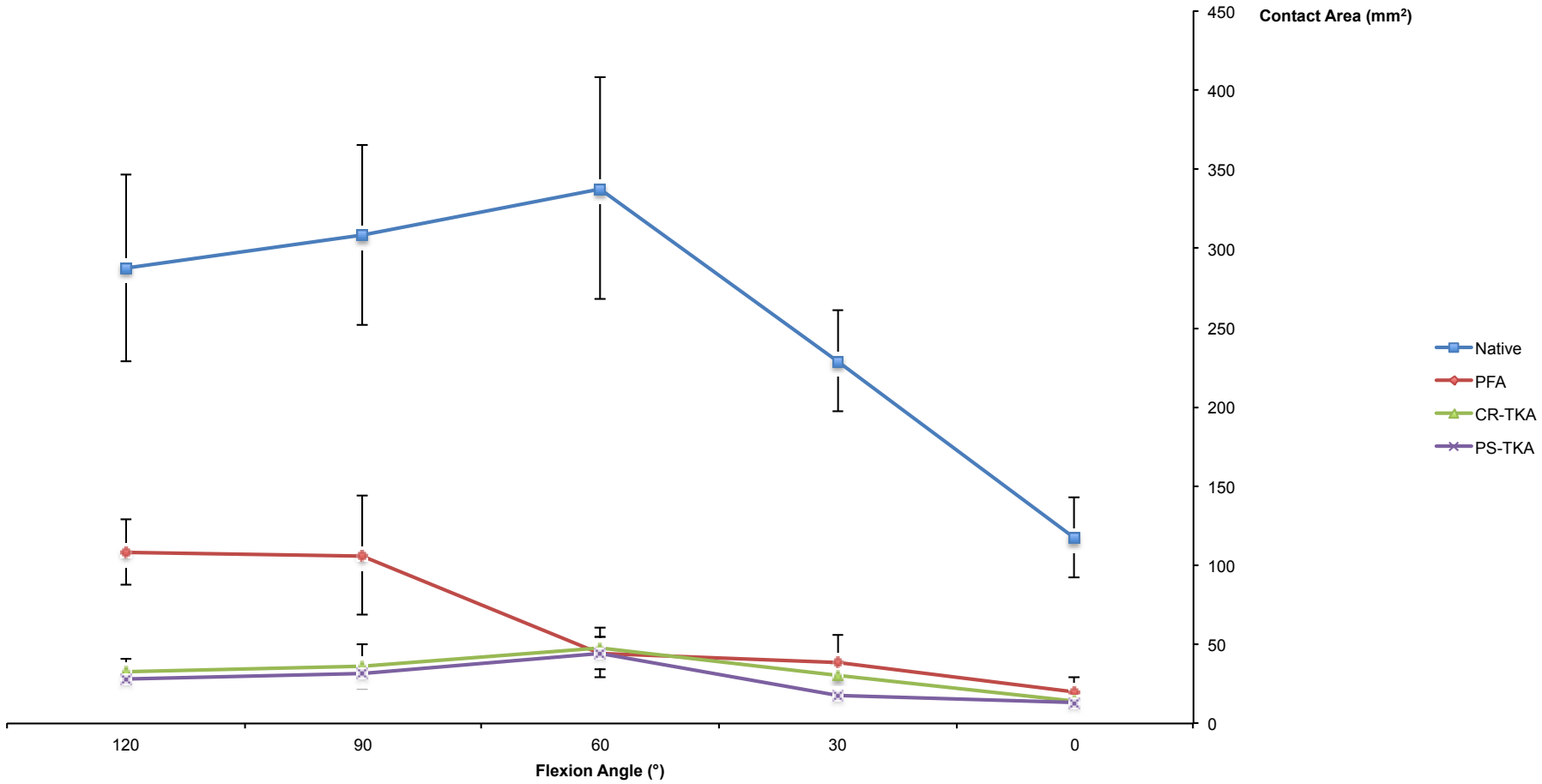


Figure 2-41 Contact Area

The contact area graph illustrates the change in contact area for all four conditions during the flexion-extension cycle. The contact area is highest for the native knee throughout the entire range of motion due to joint congruency and elastic deformation. PFA demonstrates higher contact area in deep flexion when the patellar component articulates with the native femoral condyle before transitioning to articulate with the trochlear component.

2.19.5 Results Analysis

Proof of adequate sample size

Using the Cohen's *d* equation for calculating effect size:

$$\theta = \frac{\mu_1 - \mu_2}{\sigma}$$

$\sigma = s_{pooled}$

$$s_{pooled} = \sqrt{\left[\frac{(s_1^2 + s_2^2)}{2}\right]}$$

The effect sizes calculated for randomly chosen comparisons were as follows:

EME 30° PFA = 0.1445; σ = 0.0119

EME 30° native = 0.1332; σ = 0.0120

Effect size = 0.9481

EME 80° native = 0.0786; σ = 0.0054

EME 80° PFA = 0.0660; σ = 0.0141

Effect size = 1.1780

EME 20° PFA = 0.1447; σ = 0.0172

EME 20° CR-TKA = 0.1081; σ = 0.0171

Effect size = 2.1357

(Calculations verified using PS – Power and Sample Size Calculations, software, version 3.0.0043, (Dupont & Plummer, 2009))

These effect sizes were close to the expected effect size of 1.17 thus demonstrating a similarity in data behaviour to that used to ascertain the sample size and justifying the use of the same sample size of 8 cadaveric knees. Furthermore, the large effect size of 2.13 demonstrates that a higher number of samples would not have been necessary to detect a difference between the conditions.

In summary, the key findings were:

1. Extensor mechanism efficiency (primary outcome) was greatest in the first 50° of knee flexion for all four conditions. In this range of knee flexion PFA offered the highest EME. This difference was statistically significant ($p < 0.00833$) compared with the native knee, CR-TKA and PS-TKA at 10°, 20°, 30°, 40° and 50° and also at 0° when compared with CR-TKA and PS-TKA. Conversely, in deeper flexion PFA was the least efficient at 80° of knee flexion and this finding was statistically significant when compared with the native knee and CR-TKA.

2. The resultant force produced was not different for the three arthroplasty conditions, although the trend demonstrated higher forces were generated by the PFA compared with CR-TKA and PS-TKA. The only significant differences seen were between the

native and CR-TKA and PS-TKA at 0° and between the native and all three arthroplasty conditions at 30° of knee flexion.

3. The peak pressure was comparable for all three arthroplasty conditions at 0°, 30° and 60° of knee flexion. At 90° and 120° the PFA peak pressure significantly reduced in comparison to CR-TKA and PS-TKA. There was no significant difference in peak pressure at 120° between native knee and PFA. At 0° the peak pressures for all arthroplasty conditions were relatively high.

4. The contact area results demonstrated an inverse relationship to the peak pressure, that is, an increase in contact area was associated with a decrease in peak pressure. Similarly, no difference was found between the three arthroplasty conditions at 0°, 30° and 60° of knee flexion. The contact area in the PFA condition increased significantly at 90° and 120° in comparison to CR-TKA and PS-TKA. The native knee area was significantly greater than all three arthroplasty conditions at each angle of knee flexion.

2.20 Discussion

Knee extensor mechanism function is an integral aspect of having a successful outcome following knee arthroplasty surgery. Previous studies have demonstrated weakness of the extensor mechanism hinders activities of daily living for a number of years following TKA (Berman *et al.*, 1991; Gore *et al.*, 1986; Huang *et al.*, 1996; Silva *et al.*, 2003). Some investigators have found CR-TKA to be less efficient at accommodating the weak extensor mechanism in comparison with PS-TKA due to the retention of a poor-functioning/insufficient posterior cruciate ligament (Hirsch *et al.*, 1994). However, other studies have not demonstrated a difference in quadriceps function between the two TKAs (Becker *et al.*, 1991; Bolanos *et al.*, 1998). The function of the extensor mechanism following PFA has not previously been reported. The aim of this study was to determine whether the biomechanical and geometrical differences between CR-TKA, PS-TKA and PFA result in dissimilar extensor mechanism efficiencies primarily and secondarily, whether differences in patellofemoral joint forces, peak pressures and contact areas exist between the conditions, during the flexion-extension cycle of knee motion.

The hypothesis made at the start of the study, regarding PFA EME, was as follows:

'The extensor mechanism efficiency will be greater following PFA compared with TKA throughout the range of flexion-extension cycle, 120°

to 0°. The extensor moment produced at a given quadriceps tension would be greater following PFA compared with TKA due to the more posterior tibiofemoral contact point associated with the native tibiofemoral joint resulting in a relatively longer extensor moment arm and therefore lower quadriceps force requirements and lower patellofemoral joint reaction forces.'

The results in early to mid-flexion fulfil this hypothesis. However, the relationship between knee flexion-extension cycle and EME is not linear. The relationship is more complex, appearing bimodal in distribution, which most likely reflects the changing length in extensor moment arm.

The results of this study demonstrated PFA produced greater extensor mechanism efficiency (EME) between 50° to full extension than all the other conditions. The highest mean EME, 0.1447Nm/N_{QT} (±0.0172), was seen at 20° of knee flexion for PFA and the greatest mean difference in this range, significant at $p < 0.00833$, was observed at 10° of knee flexion when compared with CR-TKA and PS-TKA, as shown in Table 2-33 and Table 2-34.

Table 2-33 Extensor mechanism efficiency mean differences: PFA versus CR-TKA

Flexion angle (°)	PFA vs CR-TKA EME Mean difference (Nm/N_{QT})	99% CI
50	0.0205	(0.0074, 0.0336)
40	0.0290	(0.0160, 0.0419)
30	0.0332	(0.0220, 0.0445)
20	0.0366	(0.0240, 0.0491)
10	0.0430	(0.0259, 0.0600)
0	0.0376	(0.0168, 0.0584)

Table 2-34 Extensor mechanism efficiency mean differences: PFA versus PS-TKA

Flexion angle (°)	PFA vs PS-TKA EME Mean difference (Nm/N_{QT})	99% CI
50	0.0266	(0.0135, 0.0397)
40	0.0351	(0.0222, 0.0481)
30	0.0327	(0.0214, 0.0440)
20	0.0325	(0.0200, 0.0451)
10	0.0424	(0.0254, 0.0594)
0	0.0415	(0.0207, 0.0623)

Unexpectedly, the PFA condition also produced significantly greater EME than the native knee in this range of motion (see Table 2-17). One possible reason for this is the PFA offset the patella more than the native knee, thus lengthening the extensor moment arm beyond its pre-existing length. Since all the knees were non-arthritic, very little bone would have been resected and therefore the possibility of increasing the offset is plausible. A large increase in extensor moment arm would in theory cause a reduction in resultant force due to the lower quadriceps force required to extend the knee. The resultant force data supports this theory when compared with the native knee results. The PFA resultant force at 60°, 30° and 0° was 71.40N (±16.47), 54.66N (±12.68) and 30.09N (±9.99), respectively, compared with the native knee data, 91.11N (±21.27), 68.64N (±9.65) and 38.28N (±4.44). However, this clear difference is not seen when compared with CR-TKA and PS-TKA despite there being a significant difference in EME at all three angles of knee flexion. The reason for this may be related to the altered knee kinematics in terms of the posterior cruciate ligament function and tibial translation during mid flexion to full extension resulting in greater magnitude of the patellar tendon force, which contributes to the resultant force.

This apparent advantage of PFA in mid flexion to full extension would theoretically make activities of daily living, which are performed in that range of motion, such as level walking, ascending and descending a slope, functionally less challenging. However, beyond this range of motion, that is, deep to mid flexion the EME of PFA was found to be lower than the other conditions and a significant difference was demonstrated at 80° when compared with the native knee and CR-TKA. This lower EME was associated with a higher resultant force, thus the extensor mechanism was much less efficient. The reason for this occurring may have been related to the new offset between the patellar button and the femoral condyle in deeper flexion, as the patellar button is no longer in articulation with the trochlear component and sits deep in the intercondylar notch. As a result, the distance between the centre of rotation (approximately the transepicondylar axis) and the patella may have been relatively shorter than that existing in the native knee, CR-TKA and PS-TKA, thus requiring a greater quadriceps force to extend the knee.

The hypothesis regarding CR-TKA and PS-TKA EME was as follows:

'There will be no difference between the extensor moment efficiency for CR-TKA compared with PS-TKA. The effect of the intact PCL in the CR-TKA compared with the cam-post mechanism will not result in a

significantly shorter extensor moment arm. Both prostheses will give rise to higher patellofemoral resultant forces than PFA or native knee.'

The results confirm the hypothesis was correct in relation to the EME; no difference was identified between CR-TKA and PS-TKA (see Table 2-17). In the experimental set up all other variables were constant, the only known geometric difference between these two prostheses is the cam-post mechanism therefore the conclusion can be drawn that no significant difference exists. This finding further corroborates previous studies that have also shown no advantage of PS-TKA over CR-TKA (Becker *et al.*, 1991; Bolanos *et al.*, 1998). It is also important to consider that the subphysiological load used in this experiment may have been too small to elicit a difference (although this is unlikely) or another possible explanation is the high kinematic variability within the CR-TKA group may have resulted in no difference being detected (Stiehl *et al.*, 1995). The bimodal variation in EME for both CR-TKA and PS-TKA throughout the flexion-extension cycle was consistent with the pattern seen with PFA and the native knee, although the degree of variation was less extreme. Differences in knee kinematics are likely to play a role but determining the specifics of this and the importance of these differences are beyond the capabilities of this experimental setup.

Contrary to the hypothesis, no statistical difference was identified between the resultant forces for PFA, CR-TKA and PS-TKA. The force data for CR-TKA and PS-TKA were not consistently higher than PFA and

the native knee. The only statistical differences detected were for the native knee, which showed greater resultant forces than CR-TKA and PS-TKA at 30° and 0°. The general trend for CR-TKA and PS-TKA resultant forces was lower than PFA and the native knee at 120°, 90°, 30° and 0°. Only at 60° knee flexion was the resultant force for both TKAs higher. The reason for this may be related to the transition point of the patellar button onto the trochlear component. Only when the patellar button comes into contact with the trochlear prosthesis does the extensor moment arm lengthen and consequentially, the resultant force decrease. Prior to that, in deep flexion, the patellar button articulates with the native femoral condyle within the intercondylar notch resulting in a shorter extensor moment arm.

The peak pressure hypothesis was as follows:

'Peak pressures will be greater for CR-TKA and PS-TKA compared with PFA and native knee throughout the range of knee flexion. The native knee will generate the lowest peak pressures.'

The data confirmed this assumption was correct. The peak pressures were consistently high for both TKAs and there was no difference between them. The hard bearing surfaces: polyethylene and cobalt chrome coupled with the non-congruent patellar button results in the transmission of a large force to a small contact area and hence high peak pressures. The native knee peak pressures were consistently

significantly lower than all three arthroplasty conditions. The main reason for this is that the force is distributed over a larger contact surface area due to the relative congruency of the native patellofemoral joint. In addition, the cartilage of the native patella and trochlea undergo elastic deformation when force is applied, which further increases the surface area. Previous research has shown that the degree of patellar cartilage deformation that occurs is dependent on the load applied (Eckstein *et al.*, 2005). In this current experiment, the load was kept constant which is reflected in the very small variations in peak pressure data for the native knee between the data recorded at each flexion angle. This interpretation also applies to the PFA data recorded in deep flexion at 120° and 90°. At these angles the patellar button articulates with the native femoral condyle. Due to the articular cartilage undergoing deformation when in contact with the patellar button, the peak pressure generated was significantly lower than CR-TKA and PS-TKA. The pressure remained greater than the native knee since the patellar button is non-conforming and the contact area significantly smaller.

Interestingly, the peak pressures at 0° were high for all the arthroplasty conditions: 7.13MPa(±1.33) (PFA), 6.69MPa(±0.89) (CR-TKA) and 6.91MPa(±1.24) (PS-TKA). Compared to the native knee peak pressure in extension (1.65MPa±0.56) these pressures are four times as high. High peak pressures have also been reported by Steinbrück *et al.*, (2013) and Becher *et al.*, (2009) with the latter study reporting 6.28MPa±2.78 for CR-TKA and 5.00MPa±2.67 for PS-TKA. In both of

these studies the patella was not resurfaced, which may explain the slightly lower pressures reported. Such high peak pressures do not mimic normal anatomy, which may explain the association with anterior knee pain following TKA (Fuchs *et al.*, 2005; Kulkarni *et al.*, 2000).

Contrary to previous studies, no difference in peak pressures was found between CR-TKA and PS-TKA. Becher *et al*., (2009) found significantly lower peak pressures with PS-TKA compared with CR-TKA over a continuous extension cycle from 120° flexion to full extension using the Genesis II system (Smith & Nephew, Memphis, Tennessee, USA). This study identified lower patellofemoral resultant force associated with PS-TKA and attributed this finding to the higher degree and more consistent posterior femoral rollback that has previously been reported. This theory is also supported by the finite element model study, which demonstrated greater posterior femoral rollback reduced patellofemoral pressure by increasing the extensor mechanism efficiency (D'Lima *et al.*, 2003). The difference in findings between the Becher *et al*., (2009) study and the current investigation are: hamstring loading, continuous dynamic motion through the extension cycle rather than at 5 angles only, different TKA prostheses (Genesis II) and physiological extension moment instead of subphysiological load. Any one of these factors may account for the differences in the results.

The contact area hypothesis was as follows:

'The contact area will be greater for PFA compared with CR-TKA and PS-TKA at higher levels of knee flexion when the patellar button begins to articulate with the native femoral condyle. There will be no difference between CR-TKA and PS-TKA. The native knee will produce the highest contact area throughout the entire range of knee flexion.'

The postulations regarding contact area for all four conditions were correct. The contact area for PFA at 90° was approximately 3 times the area seen with CR-TKA and PS-TKA (due to articulation with the native femoral condyle), and nearly a third of the contact area size seen with the native knee, as shown in Table 2-35.

Table 2-35 Mean Contact Areas at 90° flexion

Condition	Mean Contact Area at 90° flexion (mm^2)	Standard Deviation
Native knee	308.41	56.86
PFA	106.15	37.37
CR-TKA	36.29	14.13
PS-TKA	32.06	6.66

The lack of difference between CR-TKA and PS-TKA at each angle of flexion was predictable given the patellofemoral geometry and bearing surfaces were identical. This is also true for the PFA at 60°, 30° and 0°, when the patellar button transitions from native femoral condyle to articulation with the trochlear component. This is summarised in Table 2-36.

Table 2-36 Mean Contact Areas at 60°, 30° and 0° for arthroplasty conditions

Condition	Contact Area (mm^2) at 60° (mean±SD)	Contact Area (mm^2) at 30° (mean±SD)	Contact Area (mm^2) at 0° (mean±SD)
PFA	44.25 (±9.98)	38.61 (±17.50)	19.66 (±9.96)
CR-TKA	47.78 (±6.12)	30.77 (±11.70)	13.91 (±4.91)
PS-TKA	44.86 (±15.63)	17.94 (±7.89)	13.31 (±6.05)

2.21 Limitations

The main limitation of this study is the use of cadaveric knees only offers an approximation of what actual occurs *in vivo*. Therefore, applicability to the clinical setting is limited especially in this instance where the rig did not simulate stair climbing or walking involving the hip, foot and ankle motions.

The simulation of the flexion-extension cycle in this study was not continuous and did not include a weight bearing component. Static measurements at the five angles chosen in this study does not allow inference to be drawn on what is happening between those angles. Therefore, the graphical representations are assumptions of the model rather than based on exact data.

The experiments were carried out under subphysiological loads, which may have been too low to elicit a difference between the TKA conditions. Although this is unlikely because the geometry of the load-carrying specimen would not change greatly due to an increase in the load applied. Soudry *et al*. (1986) investigated the effects of varying load application/forces (partially loaded knee representing the seated position

and fully loaded simulating stair climbing) at the knee joint on femoral rollback and found the difference in TKA function to be negligible. Therefore, the extensor mechanism loaded in the physiological cross-sectional distribution and direction of pull should have been sufficient enough to detect a difference. In addition, the rationale for using subphysiological loads was a detectable difference at this load is likely to infer a difference exists at higher, physiological loads. Furthermore, the advantage of using a smaller load allowed for adequate experiment repetition while not compromising the experimental construct or causing premature sensor degradation.

The hamstrings were not loaded in this study and therefore this may have caused a degree of imbalance. Lack of hamstring loading may increase the risk of the paradoxical anterior tibial translation which may in turn change/reduce the lever arm and further reduce EME (Steinbrück *et al.*, 2013). However, Gomez-Barrena *et al*. (2010) found prosthetic geometry and cruciate function have a greater influence on changes in extensor moment arm length than the effect of the hamstrings. Since the hamstrings were unloaded for all the conditions, it is unlikely that this would have altered the comparison outcomes significantly.

Maintenance of soft tissue tension between and within condition testing was essential for accurate data acquisition. Although precautions were taken to maintain the retinaculum, such as using the transpatellar approach, inadvertent stretching or wear of the soft tissues may have

occurred during the sixteen trials per arthroplasty procedure that were carried out on each knee.

The resultant force, peak pressure and contact area were all determined using the Tekscan system. The reliability of the I-Scan sensor has been substantiated by a number of studies (Brimacombe *et al.*, 2009; Drewniak *et al.*, 2007; Gill *et al.*, 2004; Ostermeier *et al.*, 2006; Wilson *et al.*, 2003). Limitations of the sensor include the thickness (0.1mm) and sensor output (sensitivity) to alterations in humidity and temperature and over time (sensor degradation). The sensors had a tendency to crease or become damaged/degraded with repeated use because the flat sensor was not contoured to the surface being assessed. In addition, maintaining sensor position and confirming sensor orientation were frequent challenges (Beck *et al.*, 2005).

Other technical limitations that may have affected the results include the difference between calibration surface and actual test conditions. The calibration surfaces used did not mirror the actual test conditions in terms of prosthetic and native joint geometry. The calibration set up did not allow for calibration using curved surfaces. The calibration could not be performed in an actual knee as it was not feasible to carry this out in an Instron load device.

Equilibration of the sensors was not performed. Equilibration is the process of normalising the output of each sensel to the average output of all the sensels on the pad. This is accomplished by applying a known uniform pressure to all the sensels and allowing the software

to define a scale factor, which is applied to each sensel, resulting in a uniform output at that pressure. The bladder device applies the known pressure**.** Performing equilibration without this bladder device is more likely to cause unevenness of the sensor's sensitivity and thus erroneous results. However, if the same area on a sensor is loaded repeatedly, the unloaded region holds a higher sensitivity and the loaded sensels degrade over time. If equilibration is not carried out the sensor sensitivity remains uneven. The extent to which repeated loading of the same location on the sensor occurred and affected the accuracy of sensor output is unknown.

2.22 Conclusion

I believe this is the first *in vitro* study to assess the extensor mechanism efficiency following patellofemoral arthroplasty. The results show extensor mechanism efficiency was significantly greater for PFA between mid flexion to full extension (measured at 10° increments from 50° to 0°) when compared with the native knee, CR-TKA and PS-TKA. Despite previous reports in the literature, no difference was found between CR-TKA and PS-TKA to support the posterior femoral rollback theory.

Due to the nature of the study design, applicability to the clinical setting is limited. Instead, the methodology and results of this study will provide a benchmark for future, more complex studies that simulate activities of daily living and take into consideration motion at the hip, ankle and foot.

Chapter 3 Systematic Review of the Survival Proportions and Complications following the Use of Patellofemoral Arthroplasty and Total Knee Arthroplasty for the Treatment of Severe Isolated Patellofemoral Arthritis

3.1 Abstract

Objectives

Patellofemoral joint arthroplasty (PFA) and total knee arthroplasty (TKA) are both considered the most effective treatment choices for severe isolated patellofemoral arthritis. A previous meta-analysis reported higher reoperation and revision rates following PFA and suggested this may be related to prosthetic design although this hypothesis has yet to be tested. Therefore, the objectives of this study were to identify the survival and complication proportions associated with PFA using a new categorisation system based on design principles, comparing these proportions with those associated with TKA for the treatment of severe isolated patellofemoral arthritis, using systematic review methodology.

Methods

The literature was systematically reviewed to identify studies reporting survival and complication proportions following PFA or TKA for the treatment of patellofemoral arthritis with minimum follow-up of 0.5 years. The National Library of Health search engine was used to search MEDLINE from PubMed, EMBASE and CINAHL electronic bibliographic databases from date of inception to 1st June 2013. The eligibility criteria consisted of *Population*: skeletally mature patients with symptomatic isolated patellofemoral arthritis, *Intervention*: patellofemoral arthroplasty *Comparison*: total knee arthroplasty and *Outcomes*: survival data as primary outcome and complications, reoperation and functional data as

secondary outcomes. Each study was evaluated for quality using the GRADE system. Data extraction included patient demographics, prosthetic design type (grouped by a combination of design principles: inlay/onlay, symmetrical/asymmetrical, anatomical/non-anatomical, patient-specific), survival proportions and proportions of disease progression, malpositioning/misalignment, persistent pain, aseptic loosening, infection and other complications. Number of reoperations and functional outcome data were also recorded. The data was analysed within the assigned groups and comparisons were made between the groups.

Results

Forty articles met the inclusion criteria. Thirty-six of the studies were uncontrolled retrospective case series', which lowered the quality of the evidence, ranging from 'low' to 'very low' in accordance with the GRADE evaluation tool. The data could not be pooled for meta-analysis due to the clinical heterogeneity of the data and confounding effect of the variability in study designs and length of follow-up time within and between the groups.

Analysis based on design showed the inlay patellofemoral arthroplasties generally had poorer survival and complication outcomes than the onlay designs. Out of the PFA design groups the survival proportion A (revision to TKA for disease progression) and survival proportion B (any revision

for any reason) were higher in the onlay designs, ranging between 87% and 100% in the short term (0 to 5 years) compared with the range 54% to 100% associated with the inlay designs. Less data was available for mid-term (5 to 10 years) and long-term (greater than 10 years) comparison between the groups, although the inlay designs consistently demonstrated lower survival proportions in both categories. The lowest survival proportions were reported in the inlay asymmetrical non-anatomical group; long-term survival ranging from 49% to 75%. The survival proportions for the onlay, symmetrical non-anatomical group (Avon) was the most comparable to TKA. The proportion of complications and reoperations was highest in the inlay symmetrical non-anatomical group (358 complications and 265 reoperations occurred in 432 knees). Functional outcomes between the groups could not be compared due to variations in reporting. Overall, where pre- and post-operative scores were available, an improvement in function was detected.

Conclusions

This systematic review is the first to analysis the survival and complication proportions following PFA with this new design based categorisation. The results show inlay, non-anatomical designs do not give desirable outcomes. The latest onlay, anatomical design results are encouraging, although the follow-up times are relatively short and sample sizes small thus limiting the generalisability of the outcomes. The onlay,

symmetrical prosthesis provides survival proportions most comparable to TKA. The limitations of this study are considerable, such as the degree of reporting and selection biases, confounding factors and the clinical heterogeneity, and therefore weaken the conclusions drawn.

Further studies that enable data pooling without the need for standardising models are required. Ultimately, future research should consist of more robust studies in the form of a randomised clinical trial.

3.2 Introduction

The first patellofemoral joint arthroplasties (PFA) were the Lubinus and Richards I, designed in 1974 and 1975, respectively, for the treatment of severe patellofemoral arthritis. Overall, the clinical outcomes were less than satisfactory, mainly due to inappropriate patient selection and prosthetic design. Limited understanding of the biomechanics of the patellofemoral joint resulted in relatively small, inlaid femoral components with deep constraining trochlear grooves. In some instances the groove was very shallow causing the patellar component to skid about the surface of the trochlear component and maltrack. Symptoms of snapping, clunking and subluxation were not uncommonly associated with these designs. The lack of fully instrumented systems and an insufficient appreciation of the methods needed to balance the soft tissues may have also contributed to the high rates of patellar instability and anterior knee pain. These complications were the catalyst to changes in design. Newer prosthetic designs have larger medial-lateral widths, longer anterior flanges and are mainly onlay. These design modifications, along with better patient selection have led to improved clinical outcomes.

Despite these improvements, recent reports have led some surgeons to believe TKA is the gold standard treatment. The National Joint Registry for England and Wales (NJR) previously suggested the revision rate of PFA is almost four times that of TKA at 3 years (Wales, 2012). Analysis of the NJR data covering 7 years, found unexplained pain, rather than disease progression, to be the main cause of early

revision following PFA (Baker *et al.*, 2012). However, the cause of this pain and accuracy of coding could not be determined from the recorded data. Therefore, the questions regarding survival and the occurrence of specific complications associated with PFA compared with TKA, and whether these vary depending on prosthetic design, still remain unanswered.

Previous authors (Argenson, 2003; Kolettis & Stern, 1992; Leadbetter, 2008; Lonner, 2004; Montserrat, 2010; Newman, 2007) have attempted to summarise the literature although little inference can be drawn with confidence from narrative reviews (Bhandari *et al.*, 2004). A recent meta-analysis (Dy *et al.*, 2012) suggested more complications occurred following PFA and concluded that the number of complications was dependent on prosthetic design. However, the meta-analysis was performed using data with high clinical heterogeneity, which may have resulted in misleading inferences. The extent of data manipulation that was performed on this low quality data, that is, back-transform logistics regression using DerSimonian-Laird having stabilised the data using Freeman-Tukey-type arcsine square root transformation, indicates is not ideal and increases the risk of misleading data interpretation. Furthermore, the study design pooled the groups by 'generation' rather than design. This term 'generation' only bears relation to the inception date of the prosthesis and not prosthetic design features; analysis using this categorisation method can therefore be misleading. A more practical approach is to classify by design characteristics such as inlay/onlay,

symmetrical/asymmetrical, non-anatomical/anatomical and patient-specific. This allows for more appropriate comparisons to be made between the PFA prostheses and TKA and ultimately, a more accurate determination of whether complications and prosthesis survival are associated with implant design.

This systematic review is the first report to classify and assess outcomes by design principles. The aim of this study is to determine the primary outcome: survival proportion and secondary outcomes: number of complications, reoperations including revisions and functional results following PFA and TKA in patients with isolated patellofemoral arthritis.

3.3 Research Questions

The following research questions were addressed in this systematic review:

1. What are the survival proportions A and B for the six design categories of PFA compared with each other and with TKA in patients with severe isolated patellofemoral arthritis?
2. What are the proportions of the six complications associated with the six design categories of PFA compared with each other and with TKA in patients with severe isolated patellofemoral arthritis?
3. What are the reoperation occurrence and functional outcome results associated with the six design categories of PFA compared with each other and with TKA in patients with severe isolated patellofemoral arthritis?

3.4 Eligibility Criteria (PICO)

The eligibility criteria were based on the following PICO (population/intervention/comparison/outcome) and study design criteria summary.

3.4.1 Population

Skeletally mature patients who had received PFA or TKA for symptomatic isolated severe patellofemoral arthritis. The underlying diagnosis of primary arthritis- idiopathic disease, secondary arthritis due to trochlear dysplasia and other patellar instability diagnoses, trauma and other conditions resulting in isolated patellofemoral disease. Studies involving patients with greater than grade 2 tibiofemoral arthritis (bicompartmental disease) at the time of the index procedure were excluded. In addition, basic patient demographics such as age, gender, underlying diagnosis/aetiology, loss to follow-up and mean follow-up time were required to perform a meaningful analysis of the data.

3.4.2 Intervention

Commercial patellofemoral arthroplasty (cemented and uncemented) involving replacement of both the trochlear and patellar surfaces implanted in and after 1974 (year first patellofemoral prosthesis was implanted). All studies including trochlear or patellar replacement only were excluded. Intervention performed by multiple or single orthopaedic

surgeon(s); level of experience was not restricted. The arthroplasty fit into one of the following six categories:

(1) Inlay, symmetrical, non-anatomical (ISN)

(2) Inlay, asymmetrical, non-anatomical (IAN)

(3) Inlay, asymmetrical, anatomical (IAA)

(4) Onlay, symmetrical, non-anatomical (OSN)

(5) Onlay, asymmetrical, anatomical (OAA)

(6) Onlay, asymmetrical, patient-specific (OAP)

Rehabilitation following surgery followed standard local procedure and applied to all the patients within the study.

3.4.3 Comparison

Commercial total knee arthroplasty (cemented and uncemented) involving replacement of femoral and tibial surfaces +/- patellar replacement. Intervention performed by multiple or single orthopaedic surgeon(s) - level of experience was not restricted. Rehabilitation following surgery followed standard local procedure and applied to all the patients within the study.

3.4.4 Outcomes

3.4.4.1 Primary Outcome Measure

The survival proportion rather than the survival rate was chosen as the primary outcome. The true definition of rate (event/time) requires survival data for each year of follow-up. The studies available were expected to be predominantly retrospective case series' and therefore true rate data

would not have been reported. In order to accommodate this anticipated variation in reporting, without compromising the value of the inferences drawn, the survival was accurately defined and calculated as a proportion.

Specifically, two survival proportions were analysed as the primary outcome:

1. Survival Proportion A, defined as the surviving number of implants, that is, the total number of knees minus the number of knees that suffered the endpoint event - revision to TKA due to disease progression, divided by the total number of knees assessed in the sample population.
2. Survival Proportion B, as the surviving number of implants, that is, the total number of knees minus the number of knees that suffered the endpoint events - revision any reason to TKA, revision to another PFA, additional unicompartmental arthroplasty (UKA), removal of PFA or arthrodesis due to any complication (listed in secondary outcomes below), divided by the total number of knees assessed in the sample population.

The mean follow-up time for each survival proportion was also recorded so that the proportions were appropriately compared in the context of time (short-term less than 5 years, mid-term five to ten years and long-term more than 10 years).

(In the event that true survivorship analysis was performed or survival rate (event/time) was reported, these were recorded for further discussion).

3.4.4.2 Secondary Outcome Measures

Secondary outcomes consisted of complications, number of reoperations including revisions, and functional outcomes. The complications were defined as those occurring intra-operatively or post-operatively at any time point during the follow-up period. These intra- and post-operative complications were categorised into one of the following six commonly reported failure mechanisms:

1. Disease progression
2. Malpositioning/misalignment (of either the prosthesis or soft tissue imbalancing)
3. Persistent pain
4. Aseptic loosening of component(s)
5. Infection (superficial and deep)
6. Other complications- stiffness, fracture, trauma- dislocation etc.

Any reoperation that took place in the post-operative period was also recorded including revisions. All functional outcome data consisting of validated scores (such as the WOMAC score, Oxford Knee Score, Lysholm Score, American Knee Society Score, UCLA Score and Melbourne Patellar Knee Score (Bellamy *et al.*, 1988; Dawson *et al.*,

1998; Feller *et al.*, 1996; Insall *et al.*, 1989; Tegner & Lysholm, 1985; Zahiri *et al.*, 1998)) and satisfaction data reported was summarised. No radiological data was included.

3.4.5 Study Designs

Randomised clinical trial, non-randomised comparative studies-prospective and retrospective, prospective non-comparative and retrospective non-comparative studies (case series) with a minimum of 10 cases to provide true inferences from the data (Guyatt *et al.*, 2008) and with at least 0.5 years follow-up were included. All peer-reviewed articles, published in English between the inception date of each database and 1st June 2013 that met the above PICO eligibility criteria, were included. Grey literature, case reports and studies published before 1974 were excluded, since prior replacement surgery was likely to involve only a patellar prosthesis. All studies had to meet the population, intervention, comparison and primary outcome criteria to be included. If the secondary outcomes were reported in part, the study was still included providing the essential criteria were fulfilled. Studies that involved the use of more than one prosthesis were also included to identify whether the results from a 'mixed prosthesis' study were grossly different to any of the single design groups.

3.5 Material and Methods

3.5.1 Identification of Eligible Studies

The National Library of Health search engine was used to search MEDLINE from PubMed, EMBASE and CINAHL electronic bibliographic databases. These databases were chosen based on credibility and the large number of records held. In addition, searches were conducted in Web of Science and The Cochrane Library. Two independent academic and electronic systems/resources librarians evaluated the systematic search strategies and deemed them appropriate. The searches were executed on all five databases for eligible literature published between the date of their inception and 1st June 2013. In combination with the boolean operators 'AND', 'OR' and 'NOT', the following search terms were used with truncation, represented by an asterisk, to yield a greater number of results: patellofemoral joint, patell*, patellofemoral, patello-femoral, femoropatell*, femoro-patell*, arthritis, osteoarthritis, arthrosis, arthroplasty, replacement, knee and total as shown in section 3.5.2. The referenced literature in the included articles was hand searched for other eligible articles. The relevance of the referenced literature was determined by title first, followed by analysis of the abstract and then full text. All duplicates and ineligible articles were excluded. Articles that met the eligibility criteria described in section 3.4 were included.

3.5.2 Literature Search Strategy

MEDLINE

1. MEDLINE; exp PATELLOFEMORAL JOINT/; 235 results.
2. MEDLINE; (patell* OR patellofemoral OR femoropatell* OR femoro-patell* OR femor AND patell*).ti,ab; 15182
results.
3. MEDLINE; 1 OR 2; 15193 results.
4. MEDLINE; exp OSTEOARTHRITIS, KNEE/; 9066 results.
5. MEDLINE; exp ARTHRITIS/; 191754 results.
6. MEDLINE; arthrosis.ti,ab; 4191 results.
7. MEDLINE; 4 OR 5 OR 6; 193960 results.
8. MEDLINE; (patellofemoral AND arthroplasty).ti,ab; 559 results.
9. MEDLINE; (patellofemoral AND replacement).ti,ab; 256 results.
10. MEDLINE; (total AND knee AND arthroplasty).ti,ab; 9489 results.
11. MEDLINE; (total AND knee AND replacement).ti,ab; 5258 results.
12. MEDLINE; exp ARTHROPLASTY/ OR exp ARTHROPLASTY, REPLACEMENT, KNEE/ OR exp
ARTHROPLASTY, REPLACEMENT/; 35362 results.
13. MEDLINE; 8 OR 9 OR 10 OR 11 OR 12; 40040 results.
14. MEDLINE; 3 AND 7; 2037 results.
15. MEDLINE; 13 AND 14; 785 results.
16. MEDLINE; 15 [Limit to: Humans and English Language]; 718 results.

EMBASE

1. EMBASE; exp PATELLOFEMORAL JOINT/; 2405 results.
2. EMBASE; (patell* OR patellofemoral OR femoropatell* OR femoro AND patell*).ti,ab; 17070 results.
3. EMBASE; 1 AND 2; 2031 results.
4. EMBASE; exp KNEE OSTEOARTHRITIS/; 14103 results.
5. EMBASE; exp KNEE ARTHRITIS/; 2324 results.
6. EMBASE; arthrosis.ti,ab; 5199 results.
7. EMBASE; 4 OR 5 OR 6; 20952 results.
8. EMBASE; (patellofemoral AND arthroplasty).ti,ab; 616 results.
9. EMBASE; (patellofemoral AND replacement).ti,ab; 285 results.
10. EMBASE; (total AND knee AND arthroplasty).ti,ab; 11022 results.
11. EMBASE; (total AND knee AND replacement).ti,ab; 6414 results.
12. EMBASE; exp ARTHROPLASTY/ OR exp KNEE ARTHROPLASTY/; 66801 results.
13. EMBASE; exp TOTAL KNEE REPLACEMENT/; 11891 results.
14. EMBASE; 8 OR 9 OR 10 OR 11 OR 12 OR 13; 68046 results.
15. EMBASE; 3 AND 7; 346 results.
16. EMBASE; 14 AND 15; 158 results.
17. EMBASE; 16 [Limit to: Human and English Language]; 146 results.

CINAHL

1. CINAHL; exp KNEE JOINT/; 4355 results.
2. CINAHL; (patell* OR patellofemoral OR femoropatell* OR femoro AND patell*).ti,ab; 2786 results.
3. CINAHL; 1 AND 2; 606 results.

4. CINAHL; OSTEOARTHRITIS, KNEE/; 1581 results.
5. CINAHL; exp ARTHRITIS/; 25086 results.
6. CINAHL; arthrosis.ti,ab; 366 results.
7. CINAHL; 4 OR 5 OR 6; 25335 results.
8. CINAHL; (patellofemoral AND arthroplasty).ti,ab; 75 results.
9. CINAHL; (patellofemoral AND replacement).ti,ab; 60 results.
10. CINAHL; (total AND knee AND arthroplasty).ti,ab; 1781 results.
11. CINAHL; (total AND knee AND replacement).ti,ab; 1090 results.
12. CINAHL; exp ARTHROPLASTY/ OR exp ARTHROPLASTY, REPLACEMENT/ OR exp ARTHROPLASTY,
REPLACEMENT, KNEE/; 10893 results.
13. CINAHL; 8 OR 9 OR 10 OR 11 OR 12; 11194 results.
14. CINAHL; 3 AND 7; 94 results.
15. CINAHL; 13 AND 14; 45 results.
16. CINAHL; 15 [Limit to: (Language English)]; 45 results.

Web of Science

SET	Web of Science Core Collection Search History - " PhD SR PFA vs TKA"
#15	#14 AND Language=(English) *DocType=All document types; Language=All languages;*
#14	#12 AND #13 *DocType=All document types; Language=All languages;*
#13	#3 AND #7 *DocType=All document types; Language=All languages;*
#12	#8 OR #9 OR #10 OR #11 *DocType=All document types; Language=All languages;*
#11	TS=(total AND knee AND arthoplasty) OR TI=(total AND knee AND arthroplasty) *DocType=All document types; Language=All languages;*
#10	TS=(total AND knee AND replacement) OR TI=(total AND knee AND replacement) *DocType=All document types; Language=All languages;*
#9	TS=(patellofemoral AND arthroplasty) OR TI=(patellofemoral AND arthroplasty) *DocType=All document types; Language=All languages;*
#8	TS=(patellofemoral AND replacement) OR TI=(patellofemoral AND replacement) *DocType=All document types; Language=All languages;*
#7	#4 OR #5 OR #6 *DocType=All document types; Language=All languages;*
#6	TS=arthrosis *DocType=All document types; Language=All languages;*
#5	TS=arthritis *DocType=All document types; Language=All languages;*
#4	TS=knee osteoarthritis *DocType=All document types; Language=All languages;*
#3	#1 OR #2 *DocType=All document types; Language=All languages;*
#2	TS=(patell* OR patellofemoral OR femoropatell* OR femoro-patell*) *DocType=All document types; Language=All languages;*
#1	TS=patellofemoral joint *DocType=All document types; Language=All languages;*

Cochrane Online Wiley Library

ID	Search	Total
#1	patellofemoral arthroplasty OR patellofemoral replacement	67
#2	patellofemoral osteoarthritis or patellofemoral arthritis or patellofemoral arthrosis	92
#3	total knee arthroplasty or total knee replacement	2818
#4	#1 and #2	49
#5	#2 and #3	47
#6	#4 or #5	49

3.5.3 Data Extraction

Two reviewers (MJ and MFe) (see abbreviation section) independently assessed all titles and abstracts for eligibility based on the set eligibility criteria. Another reviewer (MC) was available to resolve any disparity between selected articles. A more in-depth assessment was performed on the full-texts of the selected abstracts. In the event that more than one article reported the exact same group of patients, only the most up-to-date report was included.

The data extracted by the two reviewers included study design, patient population details such as baseline demographics and aetiology, the type of prostheses used, follow-up time, prosthesis survival, number of complications, reoperations including revision, the mechanisms of failure for these revisions and functional outcome scores.

Reviewer MFe, an orthopaedic academic clinical fellow and MC, Professor of Trauma and Orthopaedic Surgery, both had previous experience in systematic reviews and therefore were appropriate to be involved in the study. Since there was no disparity between eligibility of literature included, MC did not participate in selection of the articles

assessed. Contributions made by MJ specifically included study design, data extraction from the text, figures and tables of all the eligible articles, data analysis and interpretation. Data extraction from the eligible articles was also performed by MFe. The data summaries were compared and any disparities were rechecked. Final validation of the data was performed by both MJ and MFe (the reviewers checked an equal number of articles each; the allocation of the articles was chosen at random except for the article written by MJ).

3.5.4 Quality Assessment of the Eligible Literature

Quality assessment of the selected literature was performed using the Grading of Recommendations Assessment, Development and Evaluations (GRADE) approach. This method of evaluation determined the quality of the evidence (as high, moderate, low or very low) and thus how confident we were in the results. Each study was independently appraised by both reviewers (MJ and MFe).

3.5.5 Method for Data Analysis

The clinical heterogeneity between the studies within the groups and between the groups, in terms of population/patients (e.g. patient's pre-operative history, co-morbidities), intervention (e.g. surgeon skill/technique, concomitant procedures, post-operative management), outcomes (e.g. length of follow-up) as well as unknown variables, negated pooling the data and performing a meta-analysis (see Figure 3-2).

The only data that was summarised within the groups were the patient demographics for ease of initial overview comparison. The survival and complications data were represented in weighted forest plots for all six PFA groups and TKA group. These outcomes were calculated as a proportion of the total number of knees within each individual study. The data synthesis and forest plots were generated using StatsDirect Ltd. StatsDirect statistical software. http://www.statsdirect.com. England: StatsDirect Ltd. 2013.

3.6 Results

In total, 1384 publications were identified from the search strategy (including those identified in the hand search) prior to removal of duplicates. After evaluation, 40 articles were identified as eligible for inclusion as summarised in Figure 3-1 PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) flow diagram. Thirty-seven were retrospective case series of which only one was a comparative study, two were prospective case series and one was a mixed prospective/retrospective case series. Thirty-three studies reported on the use of PFA, 6 on the use of TKA and 1 compared both treatments.

3.6.1 PRISMA Flow Diagram

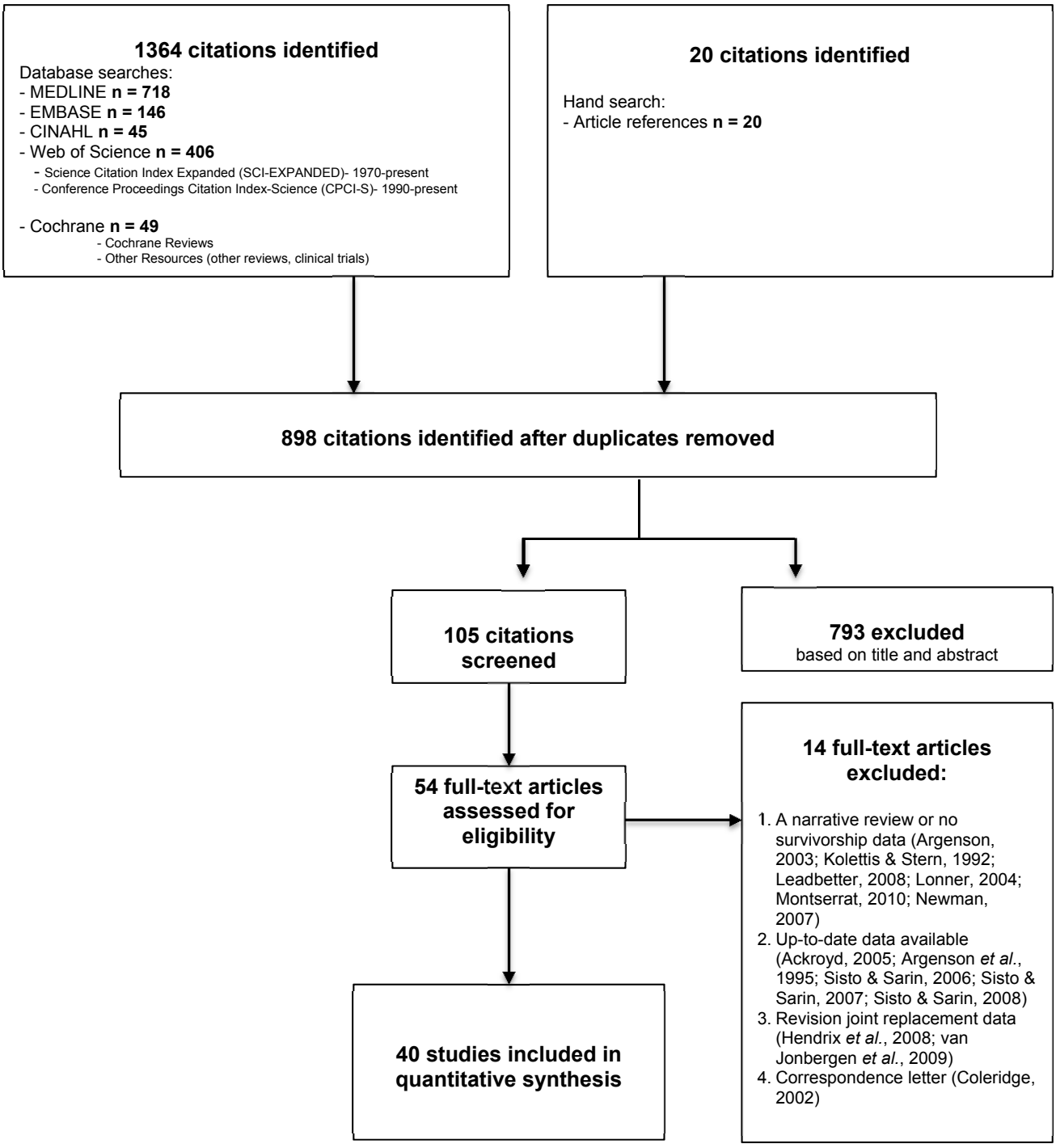


Figure 3-1 PRISMA flow diagram

3.6.2 Quality Assessment

A summary of the evaluation is shown in Table 3-1. Each category of quality assessment is further discussed below.

3.6.2.1 Study Design Limitations

Study design limitations assess the risk of bias. All the studies demonstrated 'unclear to high' risk of bias. The high likelihood of reporting and selection bias associated with uncontrolled case series' raised some concern about the results and the applicability to the general population. These potential limitations as well as the lack of a comparator group for all but one of the studies maintained the low quality rating of all of the groups assessed for both outcomes. Therefore, apart from one comparative study, the remaining uncontrolled case series' studies in the other groups were deemed as having serious study design limitations.

3.6.2.2 Inconsistency

Inconsistency is an assessment of variability or unexplained heterogeneity of the outcomes (treatment effects) between the studies within each group. The degree of heterogeneity was formally assessed using the I^2 calculation. An example of the heterogeneity is shown in Figure 3-2. This calculation shows an I^2 of 79.9%, which represents a lack of consistency and thus confirmed the data should not have been pooled for meta-analysis.

Proportion meta-analysis

Stratum	Responding	Total	
1	57	57	Blazina
2	16	16	Krajca-Radcliffe
3	24	26	de Winter
4	35	45	Kooijman
5	51	59	Cartier
6	20	20	Utukuri
7	158	181	van Jonbergen

Stratum	Proportion	95% CI (exact)		% Weights (fixed, random)		
1	1	0.94	1	14.11	15.66	Blazina
2	1	0.79	1	4.14	10.91	Krajca-Radcliffe
3	0.92	0.75	0.99	6.57	12.97	de Winter
4	0.78	0.63	0.89	11.19	14.96	Kooijman
5	0.86	0.75	0.94	14.6	15.76	Cartier
6	1	0.83	1	5.11	11.88	Utukuri
7	0.87	0.82	0.92	44.28	17.86	van Jonbergen

Fixed effects (inverse variance)
Pooled proportion = 0.9 (95% CI = 0.87 to 0.93)

Non-combinability of studies
Cochran Q = 29.83 (df = 6) P < 0.001
Moment-based estimate of between studies variance = 0.08
I^2 (inconsistency) = 79.9% (95% CI = 51.8% to 88.6%)

(StatsDirect statistical software. http://www.statsdirect.com)

Figure 3-2 Example of Heterogeneity in ISN Survival Proportion

This figure shows the degree of statistical heterogeneity found in the the ISN group for survival proportion. Represented as I^2 and Q values. Both calculations demonstrate high heterogeneity, suggesting pooling of the data is not appropriate.

The I^2 values for survival proportion A and B and complications are summarised in Appendix VI Table 6-44. The level of inconsistency demonstrated in this table shows the variation in outcome among the studies within each group. This may be secondary to the differences in clinical variables such as patient demographics and pre-intervention treatments. Due to the degree of inconsistency, each study was labelled as 'unexplained heterogeneity' and the low quality of evidence rating maintained.

3.6.2.3 Indirectness

Indirectness is the assessment of applicability of the evidence to the research questions and a determination of whether the outcomes are identified directly from a comparative study or a combination of two comparative studies. The four sources of indirectness are:

1. Differences in population applicability
2. Differences in intervention
3. Differences in outcomes
4. Indirect comparison

The sample populations in each of the studies matched the eligibility criteria and were therefore not found to be grossly different. All interventions in the studies reviewed were directly relevant. All the outcome data was obtained directly, no surrogate outcomes or endpoints were used in place of the primary outcome. All the groups were labelled as direct, except for those that did not offer any complication data and thus the low quality rating upheld.

3.6.2.4 Imprecision

Imprecision is the assessment of the investigator's confidence in the estimate of effect. Normally, the factors considered are confidence interval widths and optimal information size. Since none of the studies were randomised clinical trials or offered inferential statistics, applying this quality assessment to case series data becomes challenging. However, general observations can be made regarding sample size.

Based on the outcomes of interest, the majority of studies had reasonable sample sizes for case series'. However, two groups (which also had the lowest number of studies) inlay asymmetrical anatomical and onlay asymmetrical patient-specific had very low patient numbers- 51 and 43, respectively (see Table 3-2). Although formal optimal information size was not calculated, such low numbers are unlikely to reflect a true estimation of survival proportions in these groups. This limitation supports the low quality of evidence rating.

3.6.2.5 Publication Bias

Publication bias assessment is the detection of systematic over-estimation or under-estimation of benefit or harm of an intervention as a result of the selective publication of literature. Formal computation of publication bias was not performed for this systematic review for three reasons:

1. The heterogeneity of the data
2. Only peer-reviewed studies were included and therefore unpublished data would not have been detected based on the search strategy used. The decision not to include data from unpublished studies was based on the associated risk of introducing bias. The absence of peer-reviewing, that is, the refereeing process means there is no systematic method of vetting the quality of the study prior to inclusion in the systematic review.

3. An inadequate number of studies per group were available to assess bias using the funnel plot method

For these reasons, all the groups were rated as ‘unclear’ risk of publication bias. This risk is plausible due to the majority of the studies involved the operating surgeon(s) reporting their outcomes; failed or poor outcomes are less likely to be published. The associated risk of publication bias with this level of research maintained the low quality of evidence grading.

3.6.2.6 Overall Quality of Evidence

All the studies identified were observational and therefore automatically defined as low quality evidence. None of the quality assessment factors warranted upgrading the quality of evidence to moderate and therefore the low rating was maintained in six out of nine of the groups. The remaining three groups were further downgraded to very low for the following reasons. The inlay asymmetrical anatomical and onlay asymmetrical patient-specific groups were further downgraded because of the likely imprecision (overall small samples). The onlay asymmetrical anatomical group was downgraded due to three out of five of the studies omitting complication data.

Table 3-1 GRADE Quality Assessment of Studies

Quality Assessment										Quality
No. of Observational Studies	Study Design	Outcomes	Study Design Limitations	Inconsistency	Indirectness	Imprecision	Publication bias	No. of treated patients	No. of comparators	
Inlay, symmetrical, non-anatomical										
7	Retrospective	Survival	Yes	Yes	No	Unclear	Unclear	432	-	Low
		Complications	Yes	Yes	No	Unclear	Unclear			Low
Inlay, asymmetrical, non-anatomical										
5	Retrospective	Survival	Yes	Yes	No	Unclear	Unclear	203	-	Low
		Complications	Yes	Yes	No	Unclear	Unclear			Low
Inlay, asymmetrical, anatomical										
2	Retrospective (1)	Survival	Yes	Yes	No	Yes	Unclear	67	-	Very Low
	Retro/Prospective (1)	Complications	Yes	Yes	No	Yes	Unclear			Very Low
Onlay, symmetrical, non-anatomical										
9	Retrospective (8)	Survival	Yes	Yes	No	Unclear	Unclear	488	-	Low
	Prospective (1)	Complications	Yes	Yes	No	Unclear	Unclear			Low
Onlay, asymmetrical, anatomical										
5	Retrospective (4)	Survival	Yes	Yes	No	Unclear	Unclear	164	-	Very Low
	Prospective (1)	Complications	Yes	Yes	No	Unclear	Unclear			Very Low
Onlay, asymmetrical, patient-specific										
2	Retrospective	Survival	Yes	Yes	No	Yes	Unclear	47	-	Very Low
		Complications	Yes	Yes	No	Yes	Unclear			Very Low
Mixed group										
3	Retrospective	Survival	Yes	Yes	No	Unclear	Unclear	239	-	Low
		Complications	Yes	Yes	No	Unclear	Unclear			Low
Total knee arthroplasty										
6	Retrospective	Survival	Yes	Yes	No	Unclear	Unclear	212	-	Low
		Complications	Yes	Yes	No	Unclear	Unclear			Low
Comparison										
1	Retrospective	Survival	No	-	No	Unclear	Unclear	23	22	Low
		Complications	No	-	No	Unclear	Unclear			Low

[1]Study Design Limitations: Yes = serious limitations; No = no limitations [2]Inconsistency: Yes = unexplained heterogeneity; - = not applicable
[3]Indirectness: No = Direct [4]Imprecision: Yes = Uncertainty; Unclear = Potential uncertainty [5]Publication bias: Unclear = plausible bias

3.6.3 Study Characteristics

The specific prostheses in each category are listed in Appendix VI in Table 6-40. The numbers of studies and knees in each group varied considerably: a total of seven studies and 432 knees were included in the Inlay Symmetrical Non-anatomical (ISN) PFA group, five studies and 203 knees in the Inlay Asymmetrical Non-anatomical (IAN) PFA group, two studies and 67 knees in the Inlay Asymmetrical Anatomical (IAA) PFA group, ten studies and 511 knees in the Onlay Symmetrical Non-anatomical (OSN) PFA group, five studies and 164 knees in the Onlay Asymmetrical Anatomical (OAA) PFA group and two studies and 47 knees in the Onlay asymmetrical patient-specific (OAP) PFA group. A total of seven studies and 234 knees were included in the TKA group. Three studies had a mixture of PFA designs and were therefore combined as a separate category with a total of 239 knees. The comparative study, comprised of 23 Onlay symmetrical non-anatomical PFAs and 22 TKA, were included and analysed in the respective groups above. Across all the groups the percentage of female patients was higher than males, reflecting the known gender disparity demographics in the wider population. The mean ages and age ranges varied between the groups. For example, a twenty-year difference was found between the mean age of the OAP group (47.0 years) compared with the TKA group (67.7 years). In addition, the follow-up time differed between the groups, the ISN group had the longest mean follow-up (10.1 years) and the OAA group had the shortest (1.9 years). These differences in patient

characteristics and follow-up time were taken into consideration in the interpretation of the results, particularly the survival data. In addition, the number of lost to follow-up/excluded cases was much higher in the ISN group (over 26%) compared with all the other groups. Such high quantities of data losses are likely to introduce a degree of reporting bias. The summary demographics are shown in Table 3-2. The most common aetiology was idiopathic arthritis followed by patellar instability across all the groups that reported underlying pathology, as shown in Table 3-3.

The number of surgeons performing surgery was often not reported; where this information was recorded the number varied from single to multiple surgeons (see Appendix VI, Table 6-41). The prosthesis type and fixation method, and procedures performed prior to, concomitantly and after the index procedure, including soft tissue and bony realignment, are also recorded in Appendix VI in Table 6-41. The number of procedures performed prior to the index operation was greatest in the ISN group; a total of 513 procedures were carried out. However, this figure is disproportionately high compared to the other groups assessed.

Table 3-2 Summary of population demographics based on designated groups

Category	ISN	IAN	IAA	OSN	OAA	OAP	Mixed	TKA
Studies	7	5	2	10*	5	2	3	7*
References	(Blazina *et al.*, 1979; Cartier *et al.*, 2005; de Winter *et al.*, 2001; Kooijman *et al.*, 2003; Krajca-Radcliffe & Coker, 1996; Utukuri *et al.*, 2008; van Jonbergen *et al.*, 2010b)	(Argenson *et al.*, 2005; Board *et al.*, 2004; Smith *et al.*, 2002; Tauro *et al.*, 2001; van Wagenberg *et al.*, 2009)	(Charalambous *et al.*, 2011; Merchant, 2005)	(Ackroyd *et al.*, 2007; Hollinghurst *et al.*, 2007; Nicol *et al.*, 2006) (Dahm *et al.*, 2010; Gao *et al.*, 2010; Leadbetter *et al.*, 2009; Mont *et al.*, 2012; Odumenya *et al.*, 2010; Sarda *et al.*, 2011; Starks *et al.*, 2009)	(Beitzel *et al.*, 2013; Hofmann *et al.*, 2009; Mofidi *et al.*, 2012; Monk *et al.*, 2012; Williams *et al.*, 2013)	(Butler & Shannon, 2009; Sisto & Sarin, 2010)	(Arciero & Toomey, 1988; Arnbjörnsson & Ryd, 1998; Mohammed *et al.*, 2008)	(Dahm *et al.*, 2010; Dalury, 2005; Laskin & van Steijn, 1999; Meding *et al.*, 2007; Mont *et al.*, 2002; Parvizi *et al.*, 2001; Thompson *et al.*, 2001)
Patients	480	191	51	431	143	43	225	214
Knees	587	228	67	529	167	47	254	245
Knees LTF[§]/excluded	155	25	0	18	3	0	15	11
Remaining knees	432	203	67	511	164	47	239	234
Age (yrs)	54.3	64.8	55.5	62.4	59.8	47	60.7	67.7
Weighted Age (yrs) (mean, range)	52.5 (22.0, 90.0)	63.6 (21.0, 87.0)	58.7 (26.0, 84.0)	63.2 (27.0, 88.0)	59.1 (34.0, 84.0)	47.0 (23.0, 63.0)	60.4 (22.0, 86.0)	67.7 (44.0, 89.0)
% of females	74.9	77.1	85.2	78.1	61.6	67.3	69.8	75.1
Weighted % of females (mean, range)	67.0 (47.1, 94.1)	73.0 (54.4, 87.5)	84.3 (82.9, 87.5)	80.5 (70.5, 88.2)	62.3 (36.4, 75.0)	67.4 (61.9, 72.7)	70.5 (66.0, 75.2)	75.4 (66.7, 83.9)
Follow-up (yrs)	9.1	6.8	3.3	4.2	2.1	8.2	4.8	5.0
Weighted Follow-up (yrs) (mean, range)	10.1 (0.7, 30.6)	9.2 (0.2, 20.0)	2.9 (0.4, 6.3)	4.8 (1.0, 10.0)	1.9 (0.5, 4.3)	8.2 (3.0, 14.9)	4.8 (0.5, 13.0)	5.3 (2.0, 12.0)

*Includes data from comparative study
[§]Lost to follow-up

Table 3-3 Detailed population demographics for each study

Author Year	Study Design	Implant	No. of knees/ subjects	No. of knees/ subjects excluded	Mean age (yrs)	M:F ratio	Primary PFOA*/ Secondary PFOA-patellar instability/ Secondary PFOA-trauma/ Other Knees or subjects	Isolated (I) or ≤ Grade 2 TFOA (T)	Mean follow-up (yrs)	Lost to follow-up (LTF) or not included
Inlay, symmetrical, non-anatomical										
Blazina 1979	Retrospective	Richards I and II	85/85 57/55	28/-	39 (19-81)	-	-	I	1.8 (0.7-3.5)	28 not reviewed
Krajca-Radcliffe 1996	Retrospective	Richards I and II (Bechtol I and II)	32/25 16/13	16/12	64 (42-84)	2:11	10/1/2/0	I	5.8 (2.0-18.1)	5 LTF 4 excluded 2 deceased 1 declined
de Winter 2001	Retrospective	Richards II	35/33 26/24	9/9	59 (22-90)	5:19	18/7/1/0	T	11.1 (0.9-19.8)	9 deceased
Kooijman 2003	Retrospective	Richards II	56/51 45/43	11/8	50 (30-77)	27:24	-	T	17.0 (15.0-21.0)	7 deceased 1 excluded
Cartier 2005	Retrospective	Richards II	117/108 59/50	-/38	60 (36-81)	9:41	7/41/3/8	I	10.0 (6.0-16.0)	33 LTF 5 deceased
Utukuri 2008	Retrospective	Richards II	20/17	0	56 (43-65)	1:16	16/0/1/0	I	4.4 (2.0-7.0)	0
van Jonbergen 2010	Retrospective	Richards II	185/161 181/157	4/4	52 (±14)	59:98	138/21/22/0	T	13.3 (2.0-30.6)	4 LTF
Inlay, asymmetrical, non-anatomical										
Tauro 2001	Retrospective	Lubinus	76/59 62/48	14/11	66 (50-87)	10:49	74/0/2/0	T	7.5 (5.0-10.0)	11 deceased
Smith 2002	Retrospective	Lubinus	45/34 29/21	16/13	72 (42-86)	-	44/0/1/0	T	4.1 (0.5-7.5)	5 deceased 7 excluded 1 LTF
Board 2004	Retrospective	Lubinus	17/12	0	66 (37-82)	2:10	13/3/1/0 76/18/6/0	I	1.6 (0.2-4.7)	0
Argenson 2005	Retrospective	Autocentric	66/66 57/57	9/9	57 (21-82)	26:31	18/21/18/0	I	16.2 (12.0-20.0)	9 deceased

Van Wagenberg 2009	Retrospective	Autocentric II	24/20	0	63 (38-81)	3:21	20/0/4/0	T	4.8 (2.0-11.0)	0
Inlay, asymmetrical, anatomical										
Merchant 2005	Retrospective (8) Prospective (8)	LCS	16/16	0	47 (26-81)	2:14	0/12/2/1 1 unknown	T	4.5 (2.8-6.3)	0
Charalambous 2011	Retrospective	LCS	51/35	0	64 (47-84)	6:29	51/0/0/0	T	2.1 (0.4-5.0)	0
Onlay, symmetrical, non-anatomical										
Nicol 2006	Prospective (appears retrospective)	Avon	103/79	0	68 (46-84)	10:69	99/3/1/0 96/3/1/0	I	7.1 (5.5-8.5)	0
Ackroyd 2007	Prospective	Avon	109/85 83/63	26/22	68 (46-86)	10:75	106/2/1/0	T	5.2 (5.0-8.0)	10 deceased 5 LTF 7 excluded
Hollinghurst 2007	Retrospective (data retrieved from a database)	Avon	12/12	0	73 (55-88)	-	-	I	3.8 (2.0-4.8)	0
Leadbetter 2009	Retrospective	Avon	79/70	0	58 (34-77)	18:52	52/22/5/0	T	3.0 (2.0-5.5)	0
Starks 2009	Prospective	Avon	37/29	0	66 (30-82)	8:21	-	I	2.0 (2yr f/up)	0
Odumenya 2010	Retrospective	Avon	67/44 50/32	17/12	66 (42-88)	9:23	37/0/3/0 10 unknown	T	5.3 (2.0-10.0)	6 deceased 6 LTF
Gao 2010	Retrospective	Avon	11/11	0	54 (46-74)	2:9	11/0/0/0	I	2.0 (1.0-3.9)	0
Sarda 2011	Retrospective	Avon	45/41 44/40	1/1	62 (43-84)	13:31	-	T	4.5 (3.0-8.0)	1 deceased
Mont 2012	Retrospective	Avon	43/37	0	49 (27-67)	8:29	39/0/4/0	I	7.0 (4.0-8.0)	0
Onlay, asymmetrical, anatomical										
Hofmann 2009	Retrospective	Natural Knee II	40/34	0	61 (34-84)	-	-	I	2.5	0
Monk 2012	Retrospective	FPV	15/8	0	69 (61-80)	2:6	-	I	3.5 (1.5-4.3)	0

Mofidi 2012	Retrospective	FPV	34/28	0	-	10:18	-	I	- (0.5-1.0)	0
Williams 2013	Retrospective	FPV	53/48	0	63 (48-81)	14:34	?/34/0/0	T	2.1 (0.5-4.1)	0
Beitzel 2013	Prospective	Journey	25/25 22/22	3/3	46 (28-67)	14:8	8/14/0/0	T	2.0	1 late infection 1 converted to TKR (18m) 1 prostate Ca
Onlay, asymmetrical, patient-specific										
Butler 2009	Retrospective	Custom Performa Knee	22/21	0	49 (35-63)	8:13	12/6/4/0	I	5.0 (3.0-*nr*)	0
Sisto 2010	Retrospective	Kinematch	25/22	0	45 (23-51) @time of index PFA	6:16	-	T	11.3 (7.8-14.9)	0
Mixed group										
Arciero 1988	Retrospective	Richards II (14) CSF-Wright (11)	31/28 25/22	6/6	62 (33-86)	7:15	5/14/2/4	T	5.3 (3.0-9.0)	6 LTF
Arnbjornsson 1998	Retrospective	Richards I and II (85) Lubinus (18) Miscellaneous other (10)	-/106 113/97	-/9	63 (22-86)	33:64	83*/0/10/20 23pts had rec. dislocation	I	7.0 (3.0-13.0)	9 deceased
Mohammed 2008	Retrospective	Lubinus (46) Avon (25) FPV (30)	101/91	0	57	≈ 25:76	-	T	2.0 (0.5-8.0)	0
Total knee arthroplasty										
Meding 2007	Retrospective	AGC (26) Legacy (7)	33/27	1/1	52	6:21	-	T	6.2 (2.0-12.0)	1 deceased
Laskin 1999	Retrospective	Genesis	53/53 48/48	5/5	67 (54-85)	-	-	T	7.4 (3.0-9.5)	2 deceased 2 excluded 1 LTF
Thompson 2001	Retrospective	LCS	33/31	0	73 (58-89)	5:26	-	T	1.7	0

Mont 2002	Retrospective	Porous Coated Anatomic (9) Duracon (18) Insall-Burstein II (3)	34/27	0	73 (59-88)	9:18	-	T	6.8 (4.0-11.1)	0
Dalury 2005	Retrospective	Press Fit Condylar	33/25	0	70 (54-81)	8:17	-	T	5.2 (3.8-8.4)	0
Parvizi 2001	Retrospective	Press Fit Condylar (21) Genesis (6) Total Condylar (4)	37/29 31/24	6/5	70 (47-85)	5:19	-	I	5.2 (2.0-12.0)	4 excluded 1 declined
Comparison										
Dahm 2010	Retrospective	Avon (23)	-/23	0	60 (39-81)	-	-	T	2.4 (2.0-4.1)	0
Dahm 2010	Retrospective	Zimmer (22) SIGMA	-/22	0	69 (44-83)	-	-	T	2.3 (2.0-2.8)	0

3.6.4 Survival Proportion Outcome

Survival Proportion A (endpoint revision to TKA for disease progression) and Survival Proportion B (endpoint revision surgery to TKA for any reason, PFA, additional unicompartmental knee arthroplasty (UKA) arthrodesis or removal of prosthesis) and survivorship analysis (where reported) are recorded in Table 3-4. A general overview of the survival proportions for each group is clearly illustrated in Figure 3-3 and Figure 3-4 forest plots (corresponding with Table 3-5 and Table 3-6). Each forest plot consists of the studies analysed within a design group. The size of the black square signifies the relative proportional representation (sample size) of the study within the group. Each black square (study) has horizontal bars, which represent the confidence intervals between which the estimated mean survival proportion lies. Studies lying to the far right of the forest plot illustrate high survival proportion such as the OSN and TKA groups in Figure 3-3. In contrast, the ISN and IAN groups have lower and more varied survival proportions and this difference between the groups becomes more evident in the survival proportion B forest plots Figure 3-4. Particularly for the IAN group, the survival proportions have lowered considerably to between the 50% and 75% mark (Figure 3-4).

The following analysis assessed the data in more depth, taking into consideration the degree of variation in follow-up time within and between the groups. For example, the ISN group ranged from 1.8 years to 17 years follow-up with 78% to 100% survival proportion, whereas the OAA

group was 0.5 to 3.5 years with 92% to 100% survival proportion. A comparative evaluation of these survival proportions, without taking into account the disparity in follow-up time would be meaningless. For this reason the survival proportions results were interpreted in the context of short-term (less than 5 years), mid-term (5 to 10 years) and long-term (greater than 10 years) follow-up.

Inlay symmetrical non-anatomical

Prostheses: Richards I and II (two studies); Richards II (five studies)

Survival Proportion A: The short-term survival proportion A result for two studies (Blazina *et al.*, 1979; Utukuri *et al.*, 2008) were 100% at mean follow-up times 1.8 years and 4.4 years. The mid-term results were 100% and 86% at mean follow-up 5.8 years and 10 years, respectively (Cartier *et al.*, 2005; Krajca-Radcliffe & Coker, 1996). Beyond 10 years the survival proportion A was lower, 78%, 87% and 92% at 17.0, 13.3 and 11.1 years follow-up, respectively (de Winter *et al.*, 2001; Kooijman *et al.*, 2003; van Jonbergen *et al.*, 2010b).

Survival Proportion B: The results for survival proportion B (all reasons for revision) were lower, suggesting other reasons for failure other than disease progression were the cause. The short-term survival proportion B results varied from 87% at 1.8 years with the Richards I and II (Blazina *et al*., 1979) to 100% at 4.4 years follow-up with the Richards II (Utukuri *et al*., 2008). The main known differences between the two studies that

could have influenced the results were sample size and prostheses type. The Blazina study involved 57 knees whereas the Utukuri study only assessed 20 knees. The former study used both Richards I and II prostheses whereas the latter only implanted the Richards II. The mid-term survival proportion B in the Krajca-Radcliffe & Coker study revealed a reduction from 100% survival proportion A to 94%. Interestingly, this study also involved the use of both the Richards I and II prostheses. The number of cases reported to have malpositioning/misalignment complications in this study and the Blazina study was disproportionally higher than the proportions reported in the other studies in this group (see Table 3-10 and complications analysis section 3.6.5). The other mid-term study (Cartier *et al.*, 2005) reported a survival proportion B of 85% at 10 years; a reduction of 1% compared to survival proportion A was seen due to malpositioning/misalignment. Long-term follow-up results showed survival proportion B remained the same at 92% at 11.1 years (de Winter *et al.*, 2001), 76% at 13.3 years compared to 85% survival proportion A (van Jonbergen *et al.*, 2010b) and 62% at 17 years from 78% survival proportion A (Kooijman *et al.*, 2003). Malpositioning/misalignment and 'other' complications appeared to be associated with the decrease in survival in both of these studies, resulting in a high number of revision PFAs.

Inlay asymmetrical non-anatomical

Prostheses: Lubinus (three studies); Autocentric (one study); Autocentric II (one study)

Survival Proportion A: Three short-term follow-up studies reported survival proportion A as 71% (Autocentric II), 76% (Lubinus) and 90% (Lubinus) at 4.8, 1.6 and 4.1 years, respectively (Board *et al.*, 2004; Smith *et al.*, 2002; van Wagenberg *et al.*, 2009). The survival appears to vary considerably. Disease progression in 30% of patients as demonstrated in the former study (van Wagenberg *et al*., 2009) is very high and may be the result of poor patient selection given the presence of grade II tibiofemoral disease noted in this patient population. The mid-term results from a single study demonstrated 93% survival at 7.5 years (Tauro *et al.*, 2001) and the long-term study reported survival proportion of 75% at 16.2 years (Argenson *et al.*, 2005).

Survival Proportion B: The short-term results showed large decreases in survival 71% to 54%, 76% to 71% and 90% to 76% (Board *et al.*, 2004; Smith *et al.*, 2002; van Wagenberg *et al.*, 2009). The main cause for this decrease in all three studies was malpositioning/misalignment. The mid-term study demonstrated a 21% reduction in survival to 72% (Tauro *et al.*, 2001) due to a considerable number of knees suffering malpositioning/misalignment (15 knees) and persistent pain (7 knees) requiring revision mainly to another PFA. The long-term result was 49% at 16.2 years follow-up, reduced from 75% survival proportion A

(Argenson *et al.*, 2005). Aseptic loosening and 'other' complications were associated with this decrease in survival and led to revisions to TKA and another PFA. This group demonstrated the lowest survival proportions when compared with the other five PFA design groups and TKA. The complications resulting in the most revisions were disease progression (31 knees) and malpositioning (24 knees).

Inlay asymmetrical anatomical

Prosthesis: LCS (two studies)

Survival Proportion A: Two studies reported on the short-term outcomes of the LCS prosthesis (Charalambous *et al.*, 2011; Merchant, 2005), one of which was performed by the designing surgeon (Merchant, 2005). This article stated 100% survival proportion A at 4.5 years; the independent study reported 96% survival at 2.1 years.

Survival Proportion B: Whilst the designing surgeon's study maintained 100% survival, the independent study demonstrated a significant decrease to 67% at 2.1 years. Persistent pain was the most common complication associated with revision, occurring in 12 out of the 17 knees revised.

Onlay symmetrical non-anatomical

Prosthesis: Avon (nine studies)

Survival Proportion A: Five studies reported short-term follow-up survival data ranging from 95% to 100% between 2.0 to 4.5 years (Gao *et al.*, 2010; Hollinghurst *et al.*, 2007; Leadbetter *et al.*, 2009; Sarda *et al.*, 2011; Starks *et al.*, 2009). The four mid-term follow-up studies demonstrated 88% to 96% survival for mean follow-up time 5.2 to 7.1 years (Ackroyd *et al.*, 2007; Mont *et al.*, 2012; Nicol *et al.*, 2006; Odumenya *et al.*, 2010). No long-term follow-up studies were available for evaluation.

Survival Proportion B: There was not a large difference in the survival proportion B compared to survival proportion A, short-term follow-up results ranged from 94% to 100% and mid-term from 86% to 96%. The small decrease in survival was not associated with one specific complication. There were no reports of infection; all other complications (malpositioning/misalignment (3 knees), persistent pain (5 knees), aseptic loosening (5 knees) and other (3 knees)) contributed in comparable proportions.

Onlay asymmetrical anatomical

Prostheses: Natural Knee II (one study), Femoro Patella Vialla (three studies), Journey (one study)

Survival Proportion A: All the follow-up times for the five studies reviewed were short ranging from 0.5 years to 3.5 years (Beitzel *et al.*, 2013; Hofmann *et al.*, 2009; Mofidi *et al.*, 2012; Monk *et al.*, 2012; Williams *et al.*, 2013). Survival proportion A was 100% for all but one study, which reported survival of 92% at 2.1 years (Williams *et al.*, 2013).

Survival Proportion B: The survival proportion B remained at 100% for three of the studies (Beitzel *et al.*, 2013; Mofidi *et al.*, 2012; Monk *et al.*, 2012) with follow-up times of 0.5-1.0, 2.0 and 3.5 years. A decrease in survival from 100% to 98% at 2.5 years due to 'other' complications (2 knees) was seen in one study (Hofmann *et al.*, 2009). In another study, two knees requiring revision surgery for persistent pain resulting in a drop in survival from 92% to 87% at 2.1 years (Williams *et al.*, 2013).

Onlay asymmetrical patient-specific

Prostheses: Custom Performa Knee (one study), Kinematch (one study)

Survival Proportion A: Two customised prostheses were reviewed in this group: mid-term results of the Custom Performa Knee showed 100% survival proportion A at mean 5.0 years (Butler & Shannon, 2009) and long-term results for the Kinematch was also 100%(Sisto & Sarin, 2010).

Survival Proportion B: The Kinematch study maintained the reported 100% survival at 11.3 years, however the Custom Performa Knee study showed a drop to 95% survival proportion B due to one knee requiring revision to another PFA for an 'other' complication.

Mixed group

Prostheses: Richards I and II, CSF-Wright, Lubinus, Avon, FPV and miscellaneous other (not specified)

Survival Proportion A: The mixed group consisted of three studies involving more than six different prostheses, belonging to different design groups. One study involving the use of Lubinus, Avon and FPV reported a 96% survival proportion A at 2.0 years (Mohammed *et al.*, 2008). The mid-term results of the remaining two papers were 97% and 100% for survival proportion A at 7.0 and 5.3 years follow-up, respectively (Arciero & Toomey, 1988; Arnbjörnsson & Ryd, 1998).

Survival Proportion B: The short-term study remained at 96% survival. One mid-term study demonstrated a decrease in survival from 100% to 80%. Three revisions involving additional unicompartmental arthroplasties were performed for disease progression and two other revisions to another PFA were carried out for malpositioning. The other mid-term study survival decreased to 92% due to ten knees (out of 113 knees assessed) suffering persistent pain requiring revision surgery. Six knees

underwent another PFA, two knees had TKA surgery and one had the prosthesis removed or arthrodesed.

Total Knee Arthroplasty

Prostheses: Anatomical Graduated Component (AGC), Legacy, Genesis, Low Contact Stress (LCS), Porous Coated Anatomic, Duracon, Insall-Burstein II, Press Fit Condylar (PFC), Total Condylar

Survival Proportion B: All but one of the six studies in this group reported 100% survival proportion B (Dalury, 2005; Laskin & van Steijn, 1999; Meding *et al.*, 2007; Mont *et al.*, 2002; Thompson *et al.*, 2001). Parvizi *et al.* 2001 reported 94% survival proportion due to one case of malpositioning and another suffering aseptic loosening, both requiring revision surgery.

Comparison

Prostheses: Avon, Zimmer TKA and SIGMA

Survival Proportion: The only comparative study in this systematic review demonstrated 100% survival proportion for both the PFA and TKA groups at short-term follow-up of 2.4 and 2.3 years, respectively as shown in Table 3-5, Table 3-6, Figure 3-3 and Figure 3-4.

Table 3-4 Survival Proportions and Survivorship

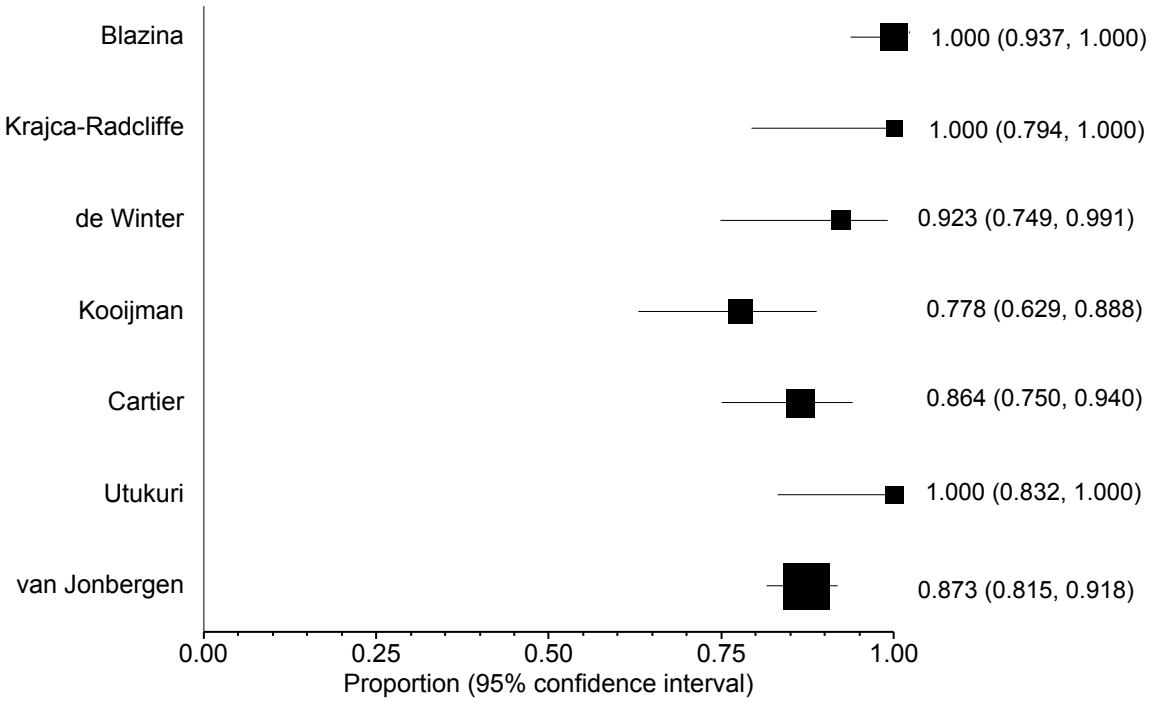
Author Year	Implant	Follow-up (yrs)	Survival Proportion (A) End point = revision to TKA for disease progression	Survival Proportion (B) End point = revision to TKA for any reason, revision to another PFA, removal of PFA or arthrodesis	Survivorship revision	Survivorship Revision any reason+pain
Inlay, symmetrical, non-anatomical						
Blazina 1979	Richards I and II	1.8	100%	87%	-	-
Krajca-Radcliffe 1996	Richards I and II	5.8	100%	94%	-	-
de Winter 2001	Richards II	11.1	92%	92%	-	-
Kooijman 2003	Richards II	17.0	78%	62%	Mean survival time (yrs) 19.5±0.45 (95%CI18.6-20)	Mean survival time 17.8±0.8 (95CI16.3-19.4)
Cartier 2005	Richards II	10	86%	85%	-	*At 6years 93.2% *At 10years 84.4% *At 11years 75.5%
Utukuri 2008	Richards II	4.4	100%	100%	-	-
van Jonbergen 2010	Richards II	13.3	87%	76%	-	At 10 years 84% (95CI78%-90%) At 20 years 69% (95CI 59%-79%)
Inlay, asymmetrical, non-anatomical						
Tauro 2001	Lubinus	7.5	93%	72%	At 8 years 65%(CI 49-77)	At 6 years 48%(CI 36-59)
Smith 2002	Lubinus	4.1	90%	76%	-	-
Board 2004	Lubinus	1.6	76%	71%	-	-
Argenson 2005	Autocentric	16.2	75%	49%	-	§At 16 years 58% (95%CI not given)
Van Wagenberg 2009	Autocentric II	4.8	71%	54%	-	-
Inlay, asymmetrical, anatomical						
Merchant 2005	LCS	4.5	100%	100%	-	-
Charalambous 2011	LCS	2.1	96%	67%	Estimated survival at 3yrs 63%(95CI47-80)	Estimated survival at 3yrs 46%(95CI30-

					median survival 3.3yrs (95CI2.2-4.5)	63) median survival 2.9yrs (95CI2.2-3.7)
Onlay, symmetrical, non-anatomical						
Nicol 2006	Avon	7.1	88%	86%	-	-
Ackroyd 2007	Avon	5.2	96%	96%	At 5yrs 95.8%(95CI91.8-99.8) (this does not take into account the 11 revisions that occurred after 5 yrs) inc. LTF at 5yrs 90.3%(95CI84.6-96)	At 5yrs 88%(95CI80.9-94.1)
Hollinghurst 2007	Avon	3.8	100%	100%	-	-
Leadbetter 2009	Avon	3.0	96%	94%	-	-
Starks 2009	Avon	2.0	100%	95%	-	-
Odumenya 2010	Avon	5.3	94%	94%	At 5yr 100%(95CI100-100) Taking into account the three failures that occurred after 5 yrs: (5.6, 5.9, 7.1) At 8yrs 89%(95CI72.9-100)	-
Gao 2010	Avon	3.0	100%	100%	-	-
Sarda 2011	Avon	4.5	95%	95%	At 4.5 yrs 95.5% CI not given	-
Mont 2012	Avon	7.0	88%	88%	At 5 yrs 95% CI not given At 7 yrs 82% CI not given	
Onlay, asymmetrical, anatomical						
Hofmann 2009	Natural Knee II	2.5	100%	98%	-	-
Monk 2012	FPV	3.5	100%	100%	-	-
Mofidi 2012	FPV	0.5-1.0	100%	100%	-	-
Williams 2013	FPV	2.1	92%	87%	At 1.8yrs 85% (CI not given)	At 1.8yrs 79% (CI not given)
Beitzel 2013	Journey	2.0	100%	100%	1 pt excluded as converted to TKR at 18m.	-

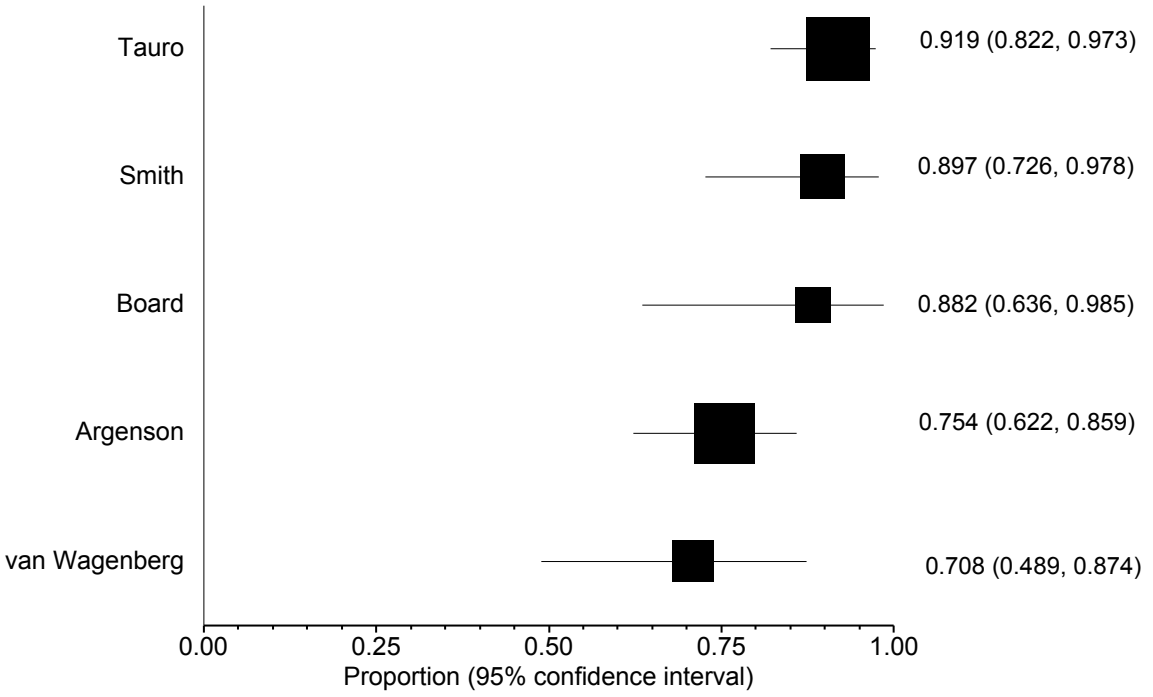
Onlay, asymmetrical, patient-specific						
Butler 2009	Custom Performa Knee	5.0	100%	95%	-	-
Sisto 2010	Kinematch	11.3	100%	100%	-	-
Mixed Group						
Arciero 1988	Richards and CSF-Wright	5.3	100%	80%	-	-
Arnbjornsson 1998	Richards I and II Lubinus Miscellaneous other	7.0	97%	92%	-	-
Mohammed 2008	Lubinus Avon FPV	2.0	96%	96%		
Total Knee Arthroplasty						
Meding 2007	AGC Legacy	6.2	-	100%	-	-
Laskin 1999	Genesis	7.4	-	100%	-	-
Thompson 2001	LCS	1.7	-	100%	-	-
Mont 2002	Porous Coated Anatomic Duracon Insall-Burstein II	6.8	-	100%	-	-
Dalury 2005	Press Fit Condylar	5.2	-	100%	-	-
Parvizi 2001	Press Fit Condylar Genesis Total Condylar	5.2	-	94%	-	-
Comparison						
Dahm 2010	Avon	2.4	100%	100%	-	-
Dahm 2010	Zimmer SIGMA	2.3	-	100%	-	-

* an extra 20 patients were contacted by phone and included in the survivorship analysis
§ includes the 9 patients who died; not including patients with pain

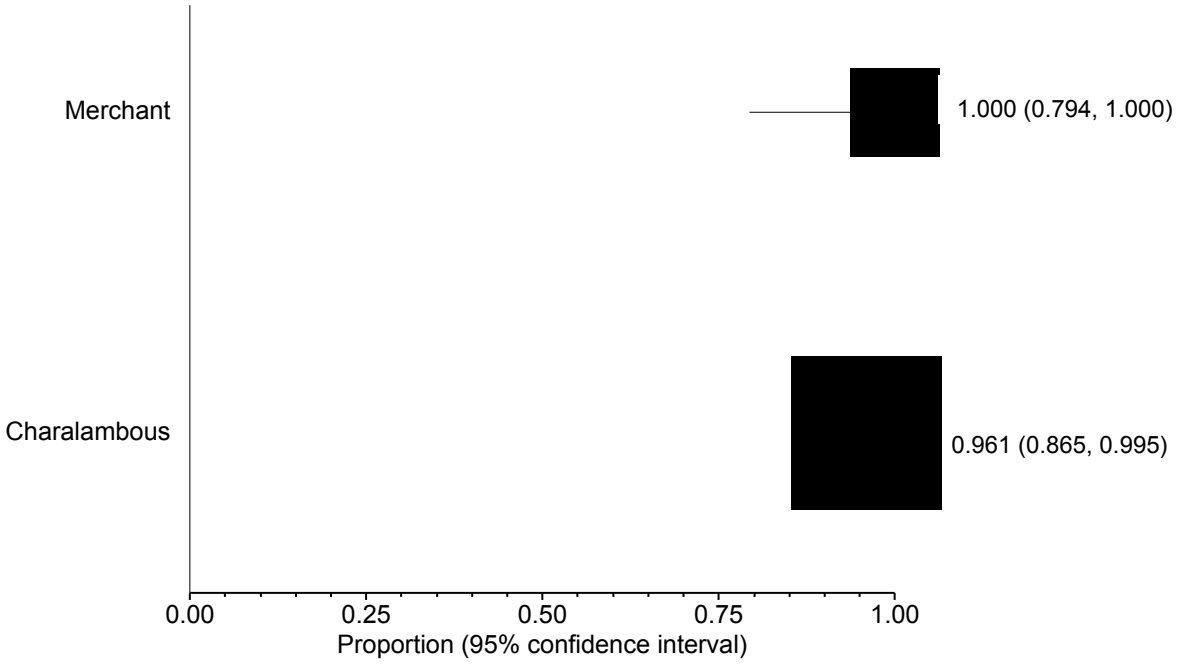
ISN survival proportion A



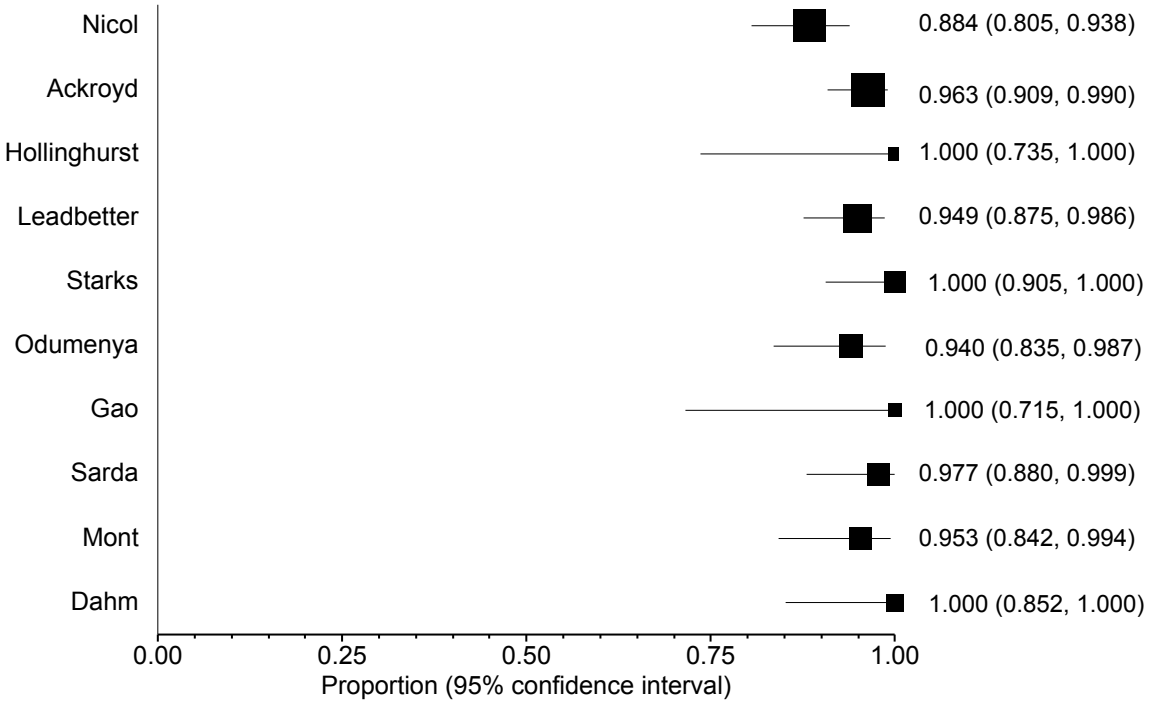
IAN Survival Proportion A



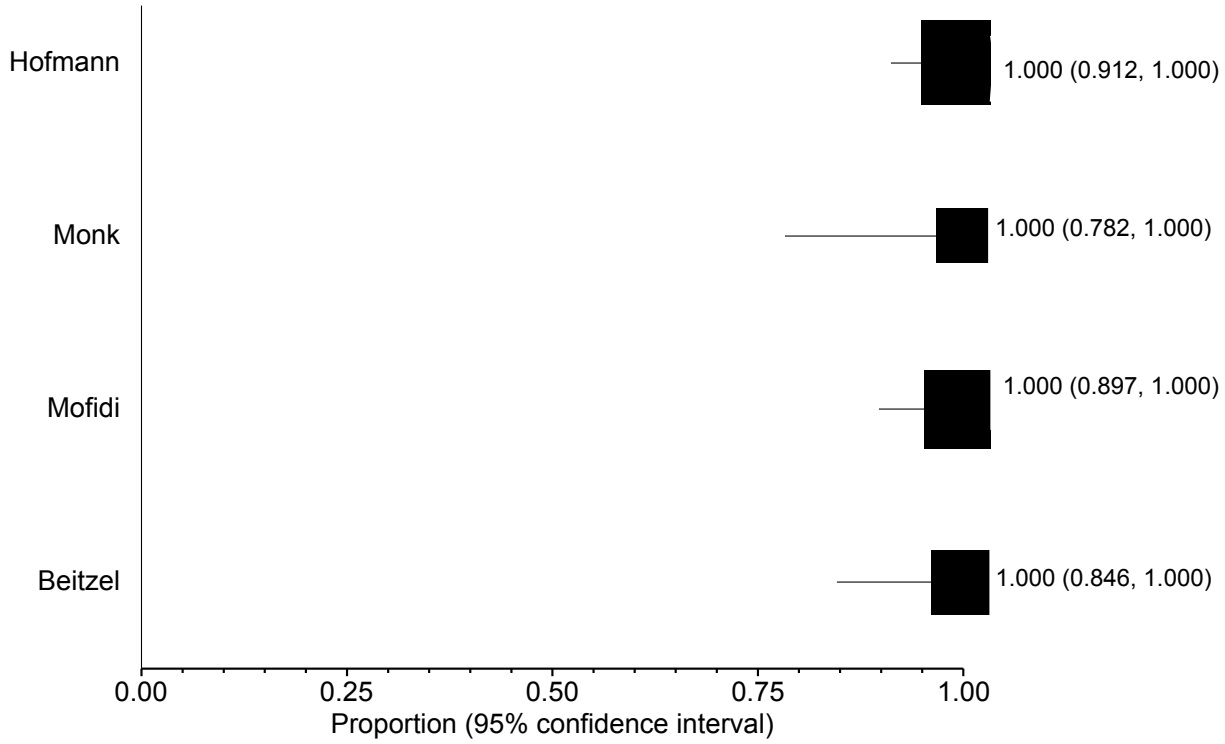
IAA Survival Proportion A



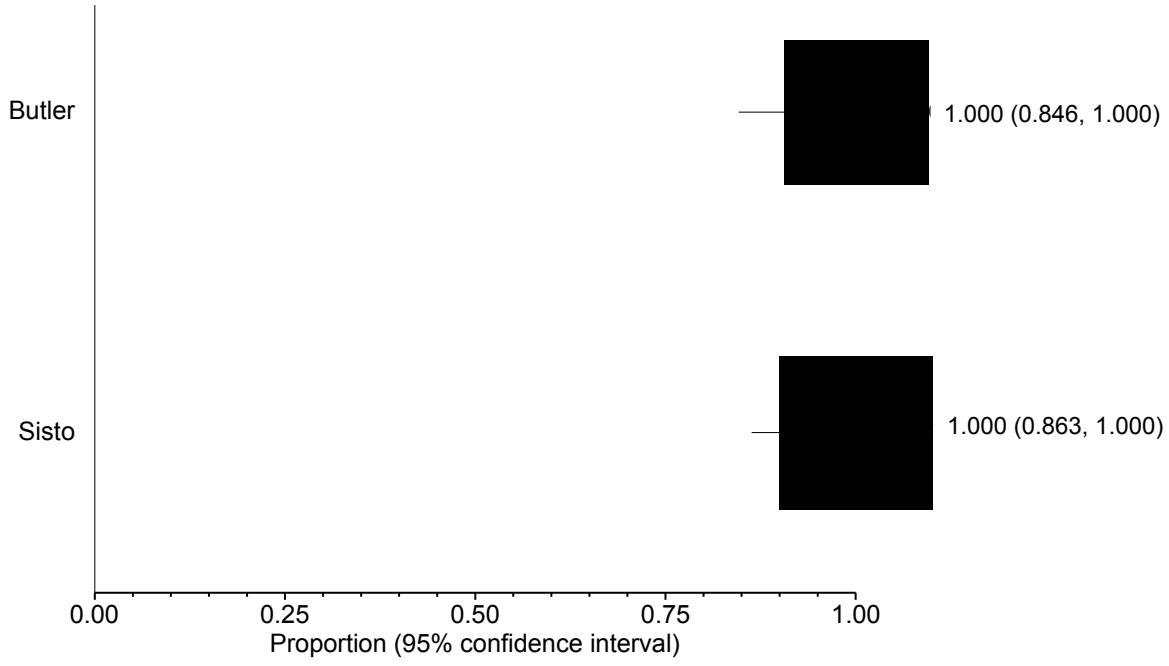
OSN Survival Proportion A



OAA Survival Proportion A



OAP Survival Proportion A



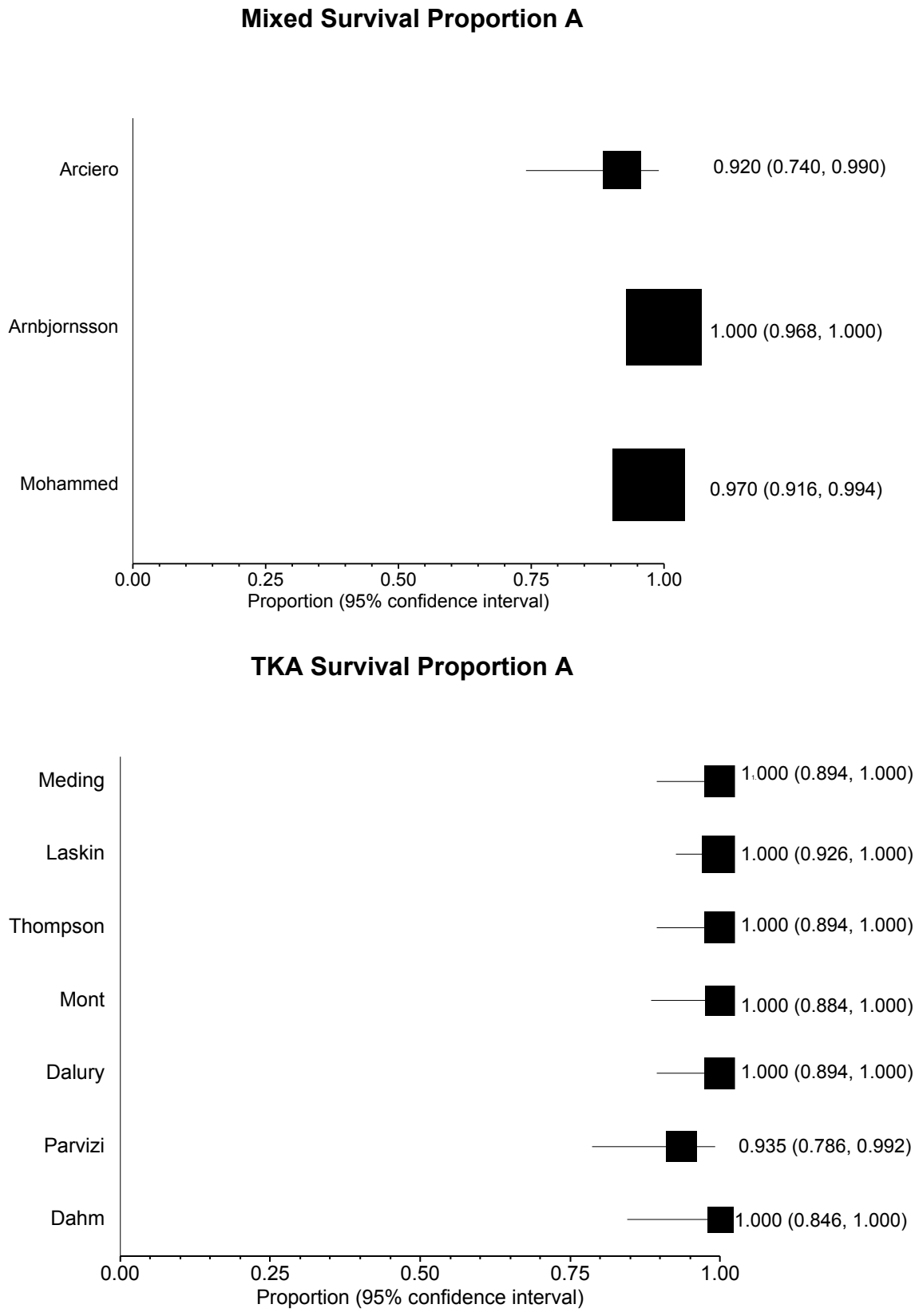


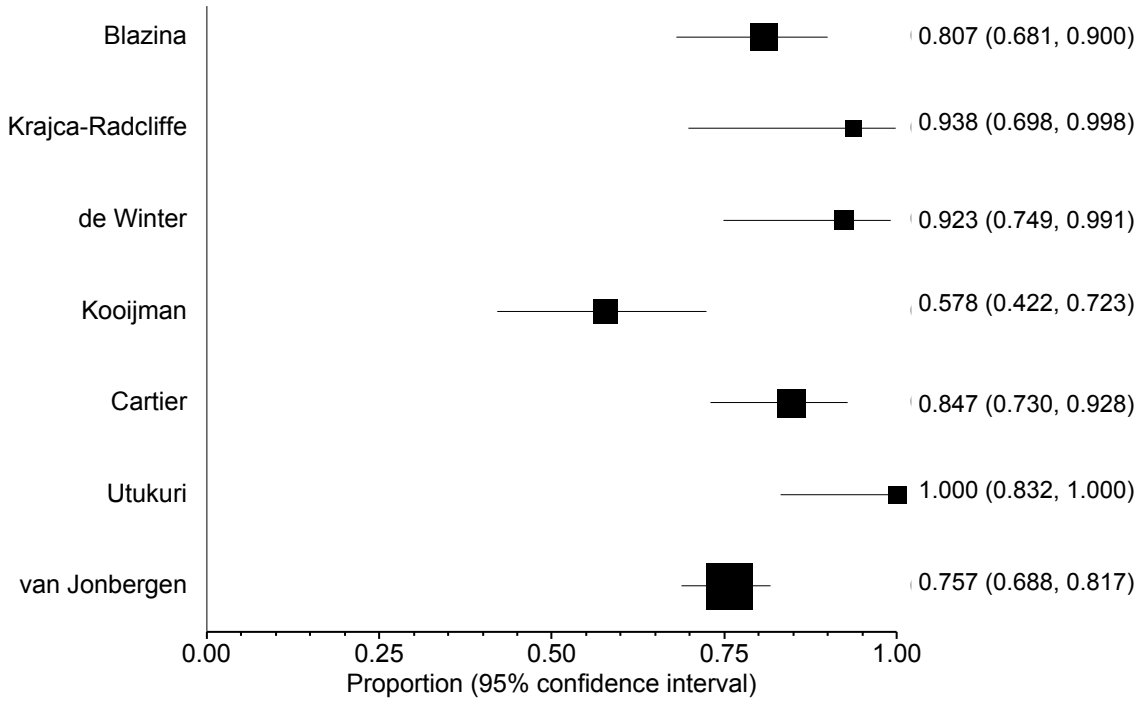
Figure 3-3 Survival Proportion A

Table 3-5 Survival Proportion A data with confidence intervals

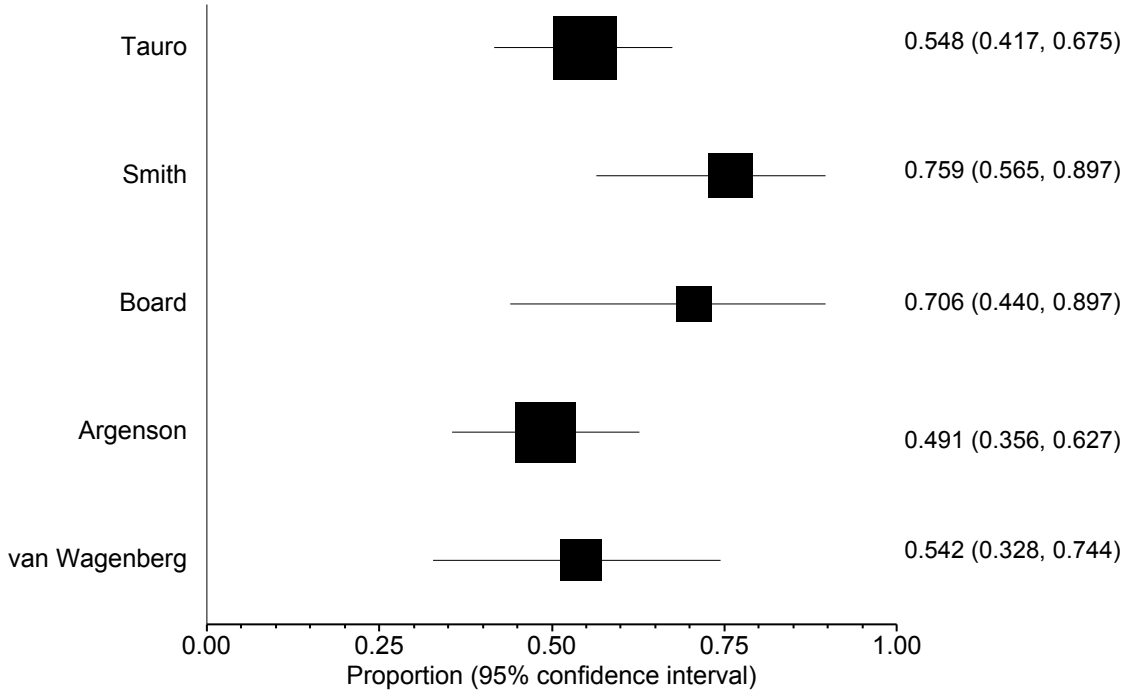
Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	1	0.94	1	14.11
Krajca-Radcliffe 1996	1	0.79	1	4.14
de Winter 2001	0.92	0.75	0.99	6.57
Kooijman 2003	0.78	0.63	0.89	11.19
Cartier 2005	0.86	0.75	0.94	14.60
Utukuri 2008	1	0.83	1	5.11
van Jonbergen 2010	0.87	0.82	0.92	44.28
IAN				
Tauro 2001	0.92	0.82	0.97	32.47
Smith 2002	0.90	0.73	0.98	15.46
Board 2004	0.88	0.64	0.99	9.28
Argenson 2005	0.75	0.62	0.86	29.90
van Wagenberg 2009	0.71	0.49	0.87	12.89
IAA				
Merchant 2005	1	0.79	1	24.64
Charalambous 2011	0.96	0.87	1	75.36
OSN				
Nicol 2006	0.88	0.81	0.94	19.96
Ackroyd 2007	0.96	0.91	0.99	21.10
Hollinghurst 2007	1	0.74	1	2.50
Leadbetter 2009	0.95	0.88	0.99	15.36
Starks 2009	1	0.91	1	7.29
Odumenya 2010	0.94	0.83	0.99	9.79
Gao 2010	1	0.72	1	2.30
Sarda 2011	0.98	0.88	1	8.64
Mont 2012	0.95	0.84	0.99	8.45
Dahm 2010	1	0.85	1	4.61
OAA				
Hofmann 2009	1	0.91	1	35.65
Monk 2012	1	0.78	1	13.91
Mofidi 2012	1	0.90	1	30.44
Beitzel 2013	1	0.85	1	20.00
OAP				
Butler 2009	1	0.85	1	46.94
Sisto 2010	1	0.86	1	53.06
Mixed				
Arciero 1988	0.92	0.74	0.99	10.74
Arnbjornsson 1998	1	0.97	1	47.11
Mohammed 2008	0.97	0.92	0.99	42.15
TKA				
Meding 2007	1	0.89	1	14.35
Laskin 1999	1	0.93	1	20.68
Thompson 2001	1	0.89	1	14.35
Mont 2002	1	0.88	1	13.08
Dalury 2005	1	0.89	1	14.35
Parvizi 2001	0.94	0.79	0.99	13.50
Dahm 2010	1	0.85	1	9.71

*number of knees that were not revised to TKA for disease progression divided by the total number of knees assessed

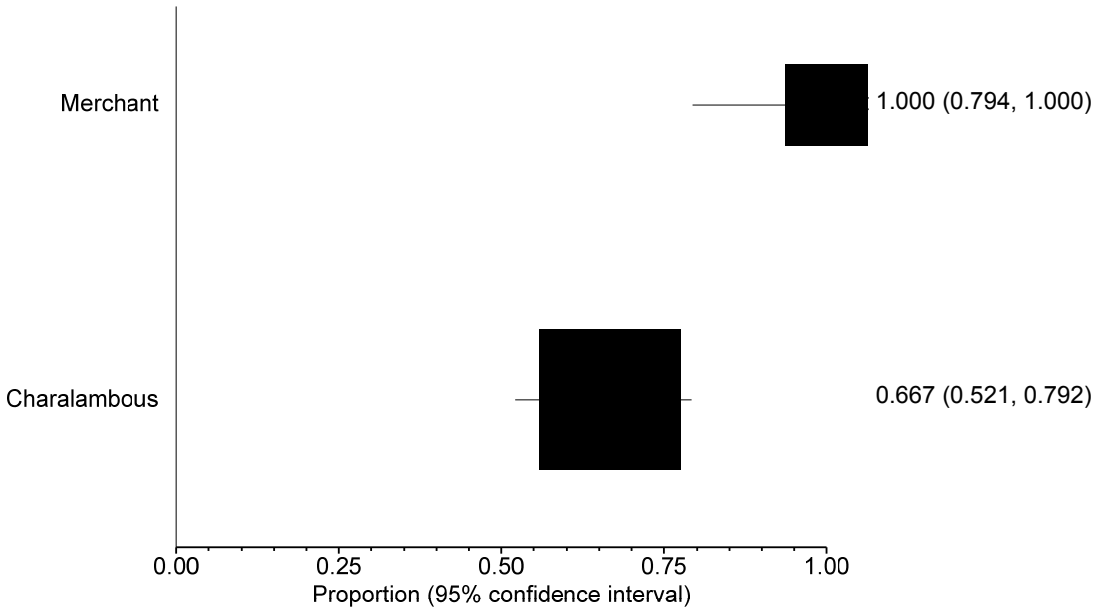
ISN Survival Proportion B



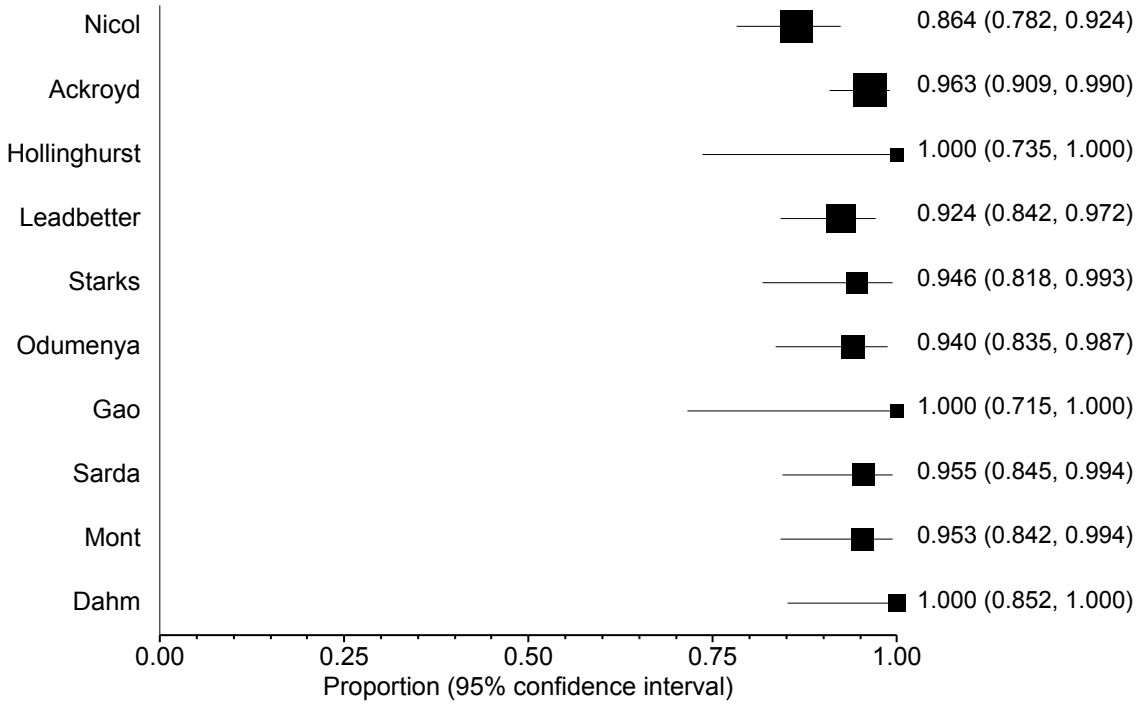
IAN Survival Proportion B



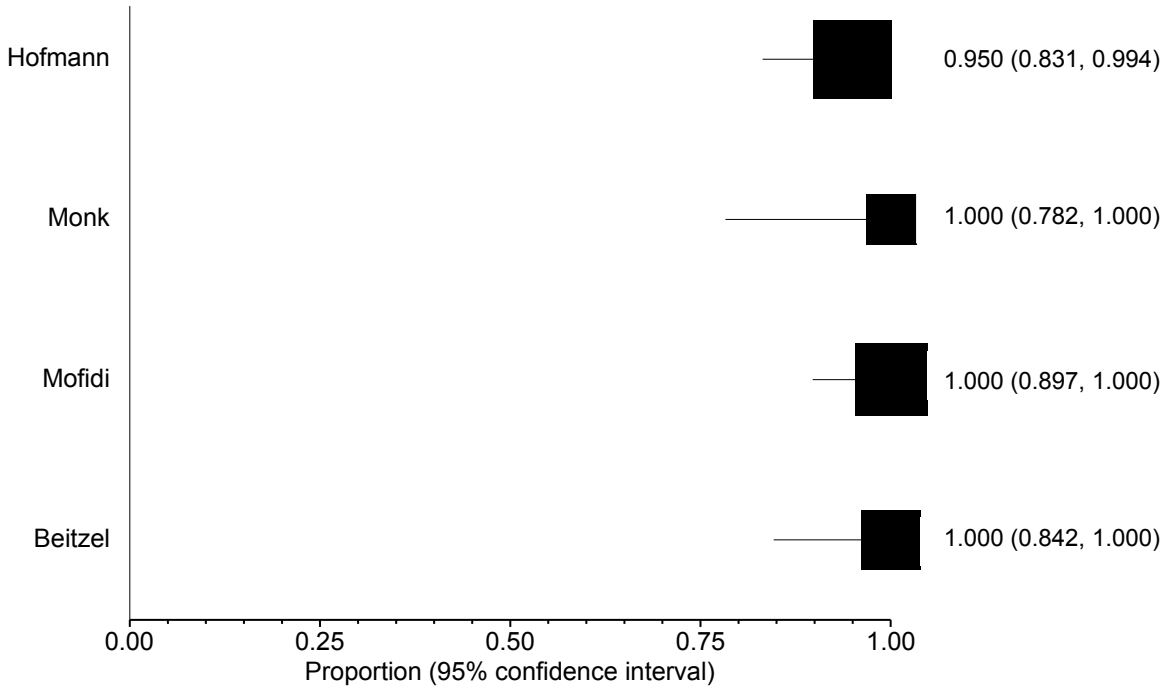
IAA Survival Proportion B



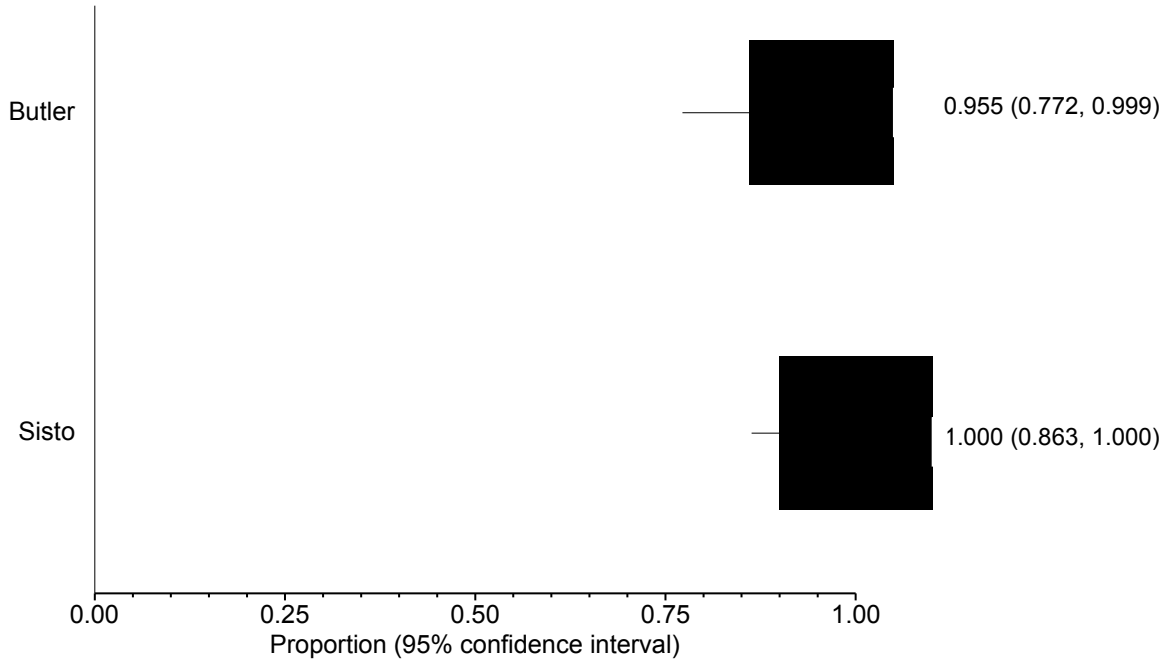
OSN Survival Proportion B



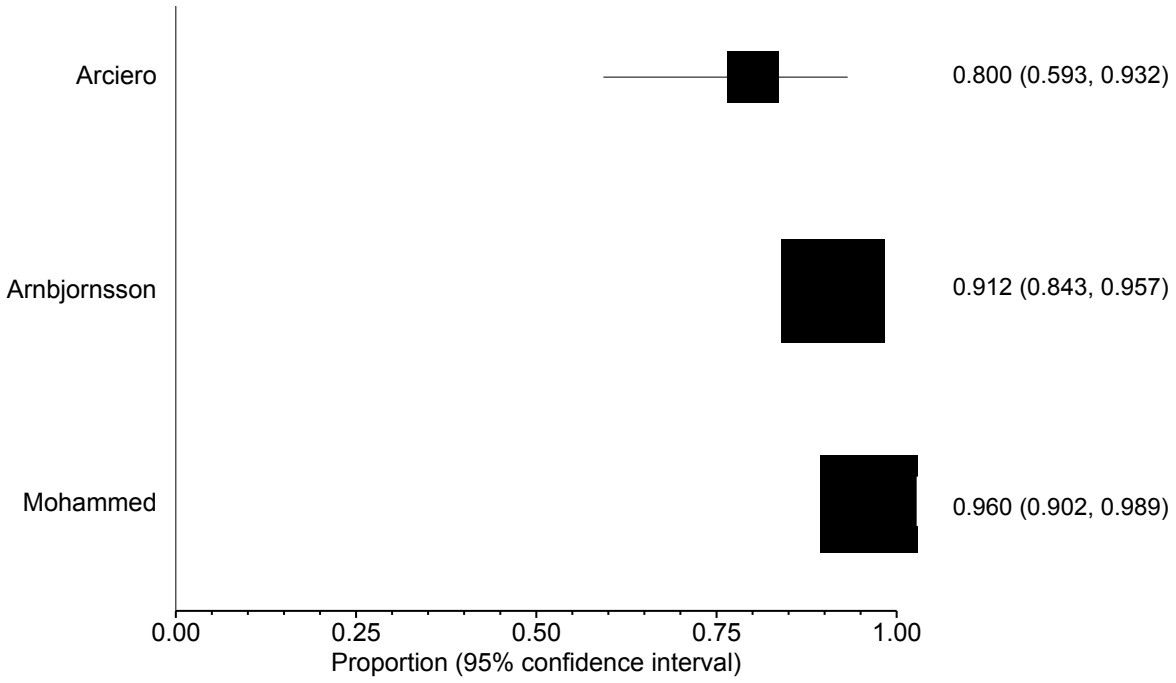
OAA Survival Proportion B



OAP Survival Proportion B



Mixed Survival Proportion B



TKA Survival Proportion B

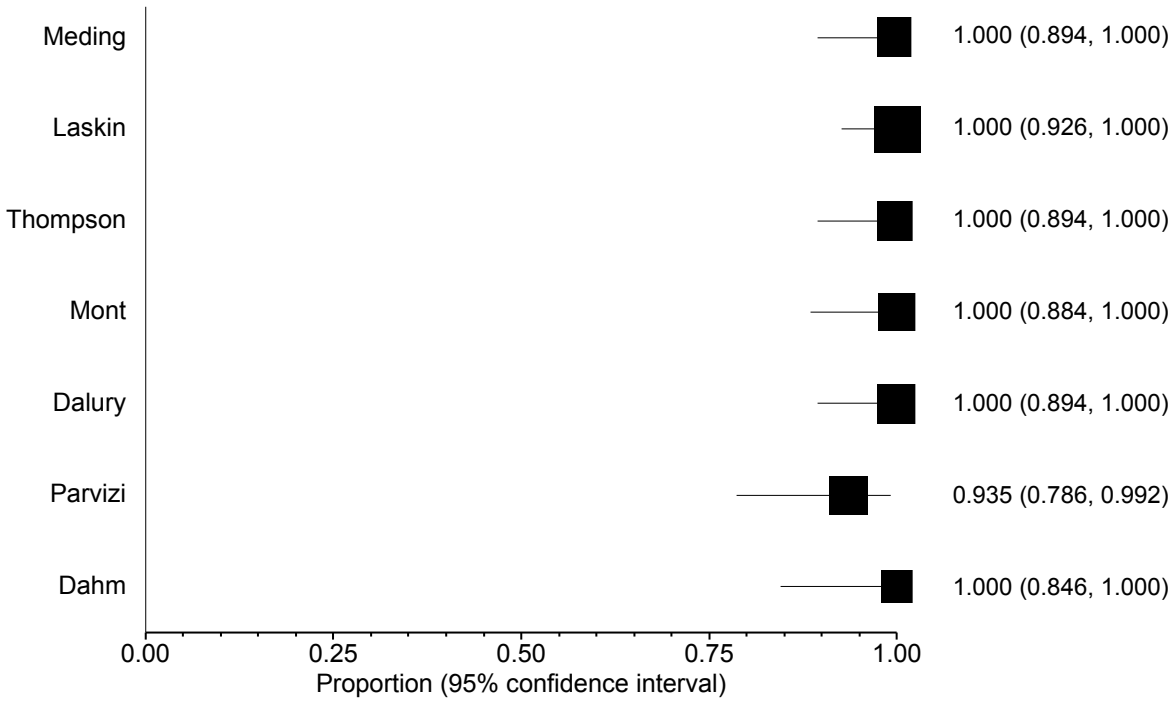


Figure 3-4 Survival Proportion B

Table 3-6 Survival Proportion B data with confidence intervals

Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0.81	0.68	0.90	14.11
Krajca-Radcliffe 1996	0.94	0.70	1	4.14
de Winter 2001	0.92	0.75	0.99	6.57
Kooijman 2003	0.58	0.42	0.7	11.19
Cartier 2005	0.85	0.73	0.93	14.60
Utukuri 2008	1	0.83	1	5.11
van Jonbergen 2010	0.76	0.69	0.82	44.28
IAN				
Tauro 2001	0.55	0.42	0.68	32.47
Smith 2002	0.76	0.56	0.90	15.46
Board 2004	0.71	0.44	0.90	9.28
Argenson 2005	0.49	0.36	0.63	29.90
van Wagenberg 2009	0.54	0.33	0.74	12.89
IAA				
Merchant 2005	1	0.79	1	24.64
Charalambous 2011	0.67	0.52	0.79	75.36
OSN				
Nicol 2006	0.86	0.78	0.92	19.96
Ackroyd 2007	0.96	0.91	0.99	21.11
Hollinghurst 2007	1	0.74	1	2.50
Leadbetter 2009	0.92	0.84	0.97	15.36
Starks 2009	0.95	0.82	0.99	7.29
Odumenya 2010	0.94	0.83	0.99	9.79
Gao 2010	1	0.72	1	2.30
Sarda 2011	0.95	0.85	0.99	8.64
Mont 2012	0.95	0.84	0.99	8.45
Dahm 2010	1	0.85	1	4.61
OAA				
Hofmann 2009	0.95	0.83	0.9	35.65
Monk 2012	1	0.78	1	13.91
Mofidi 2012	1	0.90	1	30.43
Beitzel 2013	1	0.85	1	20.01
OAP				
Butler 2009	0.95	0.77	1	46.94
Sisto 2010	1	0.86	1	53.06
Mixed				
Arciero 1988	0.8	0.59	0.9	10.74
Arnbjornsson 1998	0.91	0.84	0.96	47.11
Mohammed 2008	0.96	0.90	0.99	42.15
TKA				
Meding 2007	1	0.89	1	14.35
Laskin 1999	1	0.93	1	20.68
Thompson 2001	1	0.89	1	14.35
Mont 2002	1	0.88	1	13.08
Dalury 2005	1	0.89	1	14.35
Parvizi 2001	0.94	0.79	0.99	13.50
Dahm 2010	1	0.85	1	9.70

*number of knees that were not revised to TKA for disease progression, PFA, arthrodesed or metal work removed divided by the total number of knees assessed

3.6.5 Complications and Reoperations

All complications, including reoperations were summarised in Table 3-8 based on the six previously described modes of failure listed in section 3.4.4.2. The number of reoperations, and number and type of revisions were recorded in Table 3-7. Mechanisms of failure for all the revisions were recorded in Appendix VI in Table 6-42. The complication data was also presented as forest plots for all six mechanisms in the same format as the survival data. Studies towards the far left of the forest plots exemplified low or no occurrence of the complication. Those that were towards the right demonstrated a high occurrence of the complication. For example, disease progression appears to have been reported frequently in the ISN, IAN and OSN groups as illustrated in Figure 3-5. In contrast, the occurrence of infection was very low or zero for the majority of studies in all the groups as illustrated in Figure 3-9.

Inlay symmetrical non-anatomical

Prostheses: Richards I and II (two studies); Richards II (five studies)

The most common complications reported in this group were malpositioning/misalignment, 'other' complications and disease progression, in order of frequency. Figure 3-5, Figure 3-6 and Figure 3-10 forest plots illustrated the high proportion of these complications compared with the other groups. Blazina *et al.* (1979) stated 54% (46 out of 85) of the knees assessed had malpositioning and Krajca-Radcliffe &

Coker (1996) found 94 % (15 out of 16 knees) had malpositioning/misalignment. The remaining five studies in this group reported lower numbers of this complication, ranging from 0% to 10% of the knees assessed. This distinguishable difference between the studies may be related to the prostheses used; these five studies only involved the use of the Richards II whereas the other two studies used both Richards I and II.

While taking into account this group had the largest patient population, the number of complications reported was still disproportionally higher than that found in all the other groups analysed. Two of the studies (Blazina *et al.*, 1979; van Jonbergen *et al.*, 2010b) in this group reported over 100 complications of which one study had only 1.8 years follow-up (Blazina *et al*., 1979). The majority of these complications required operative management, as shown in Table 3-7 and Table 3-8.

Despite the high proportion of malpositioning/misalignment cases, disease progression was the most common mode of failure in this group. Forty-three knees were converted to TKA for disease progression compared with 30 knees that required revision surgery for malpositioning/misalignment.

Inlay asymmetrical non-anatomical

Prostheses: Lubinus (three studies); Autocentric (one study); Autocentric II (one study)

The most common mode of failure requiring revision surgery was disease progression (see Table 3-7). However, malpositioning/misalignment was the commonest complication; 57 cases were reported of which 24 patients required operative management. A high number of 'other' complications were also reported (41 cases), such as diagnostic arthroscopy/debridement, patella fracture, stiffness, manipulation under anaesthesia and lateral patellar facet resection.

Inlay asymmetrical anatomical

Prosthesis: LCS (two studies)

Disease Progression was the most frequently recorded complication but not the main cause of revision. Persistent pain was the most common mechanism of failure resulting in all 12 cases with this complication requiring revision surgery to TKA.

Onlay symmetrical non-anatomical

Prosthesis: Avon (nine studies)

Disease progression was the most common mode of failure requiring revision surgery and the most frequently reported complication in this group. Although many of the patients had dual pathology, 26 out of 33 knees that underwent revision surgery were revised to TKA due to disease progression (see Table 3-7). A similar number of cases reported malpositioning (12 knees), persistent pain (13 knees) and other complications (18 knees). All five cases of aseptic loosening were revised. There were no cases of infection.

Onlay asymmetrical anatomical

Prostheses: Natural Knee II (one study), Femoro Patella Vialla (three studies), Journey (one study)

Fewer complications were reported, although this observation is likely to have been influenced by the relatively shorter follow-up and smaller patient population in this group. The majority of the complications (14 out of 18) were reported by the largest study in the group (Williams *et al.*, 2013). The main complications were persistent pain, disease progression and 'other', in order of frequency. There was one case of infection that did not require revision surgery.

Onlay anatomical patient-specific

Prostheses: Custom Performa Knee (one study), Kinematch (one study)

Only two studies were included in this category. Eight 'other' complications were reported by one study of which one knee required revision to another PFA (Butler & Shannon, 2009). These complications consisted of arthrofibrosis, patellar component wear and fracturing and occurred in a third of the patients observed. The other study reported no complications in the 25 patients at mean 11.3 years follow-up (Sisto & Sarin, 2010).

Mixed group

Prostheses: Richards I and II, CSF-Wright, Lubinus, Avon, FPV and miscellaneous other (not specified)

Ten revisions were performed for persistent pain, whereas six were carried out for disease progression. The 'other' category was the most common complication (such as patellectomy, arthroscopy, MUA, lateral release), followed by persistent pain and malpositioning/misalignment. The total reoperation number for this group was also relatively high, 107 reoperations were performed of which 18 were for revision surgery (only three TKAs were carried out for disease progression). This is shown in Table 3-7 and Table 3-8.

Total knee arthroplasty

Prostheses: Anatomical Graduated Component (AGC), Legacy, Genesis, Low Contact Stress (LCS), Porous Coated Anatomic, Duracon, Insall-Burstein II, Press Fit Condylar (PFC), Total Condylar

Out of the 208 knees assessed in this group only two required revision surgery to TKA, one for malpositioning and the other for persistent pain. Both these cases were from the same study (Parvizi *et al.*, 2001). The main complication in this group was malpositioning associated with the Genesis prosthesis (Laskin & van Steijn, 1999; Parvizi *et al.*, 2001) as recorded in Table 3-8 and illustrated in the forest plot Figure 3-6.

Comparison

Prostheses: Avon, Zimmer TKA and SIGMA

There were only two complications in the TKA group of patients, both were categorised as 'other' (one required manipulation for stiffness and the other suffered a deep vein thrombosis). No revision surgery was required in either group of patients.

Table 3-7 Number of Reoperations and Revisions

Author Year	Implant	Number of Reoperations	Revisions to TKA for disease progression	Revisions to TKA for other pathology	Revisions to PFA	Additional UKA	Removal of prosthesis/arthrodesis
Inlay, symmetrical, non-anatomical							
Blazina 1979	Richards I and II	101	0	0	9	0	2
Krajca-Radcliffe 1996	Richards I and II	4	0	0	1	0	0
de Winter 2001	Richards II	12	2	0	0	0	0
Kooijman 2003	Richards II	30	10	0	7	0	2
Cartier 2005	Richards II	13	8	0	1	0	0
Utukuri 2008	Richards II	0	0	0	0	0	0
van Jonbergen 2010	Richards II	105	23	0	18	0	3
Inlay, asymmetrical, non-anatomical							
Tauro 2001	Lubinus	36	5	6	10	0	0
Smith 2002	Lubinus	10	3	2	2	0	0
Board 2004	Lubinus	7	2	2	1	0	0
Argenson 2005	Autocentric	36	14	8	7	0	0
Van Wagenberg 2009	Autocentric II	26	7	0	4	0	0
Inlay, asymmetrical, anatomical							
Merchant 2005	LCS	0	0	0	0	0	0

Charalambous 2011	LCS	18	2	14	1	0	0
Onlay, symmetrical, non-anatomical							
Nicol 2006	Avon	14	12	2	0	0	0
Ackroyd 2007	Avon	8	4	0	0	0	0
Hollinghurst 2007	Avon	0	0	0	0	0	0
Leadbetter 2009	Avon	7	4	2	0	0	0
Starks 2009	Avon	2	0	0	2	0	0
Odumenya 2010	Avon	4	3	0	0	0	0
Gao 2010	Avon	0	0	0	0	0	0
Sarda 2011	Avon	10	1	1	0	0	0
Mont 2012	Avon	11	2	0	0	0	0
Onlay, asymmetrical, anatomical							
Hofmann 2009	Natural Knee II	4	0	0	2	0	0
Monk 2012	FPV	0	0	0	0	0	0
Mofidi 2012	FPV	0	0	0	0	0	0
Williams 2013	FPV	8	4	2	1	0	0
Beitzel 2013	Journey	0	0	0	0	0	0
Onlay, asymmetrical, patient-specific							
Butler 2009	Custom Performa Knee	3	0	0	1	0	0

Sisto 2010	Kinematch	0	0	0	0	0	0
Mixed group							
Arciero 1988	Richards and CSF-Wright	11	0	0	2	3	0
Arnbjornsson 1998	Richards I and II Lubinus Miscellaneous other	61	0	3	6	0	1
Mohammed 2008	Lubinus Avon FPV	35	3	1	0	0	0
Total knee arthroplasty							
Meding 2007	AGC Legacy	0	0	0	0	0	0
Laskin 1999	Genesis	0	0	0	0	0	0
Thompson 2001	LCS	0	0	0	0	0	0
Mont 2002	Porous Coated Anatomic Duracon Insall-Burstein II	1	0	0	0	0	0
Dalury 2005	Press Fit Condylar	0	0	0	0	0	0
Parvizi 2001	Press Fit Condylar Genesis Total Condylar	4	0	2	0	0	0
Comparison							
Dahm 2010	Avon	0	0	0	0	0	0
Dahm 2010	Zimmer SIGMA	1	0	0	0	0	0

Table 3-8 Summary of all Complications

Author Year	Implant	Knees	Disease Progression (TFOA)	Number of Malposition/ misalignment	Number of persistent pain	Aseptic loosening	Infection	Other (stiffness, trauma etc)
Inlay, symmetrical, non-anatomical								
Blazina 1979	Richards I and II	85	0	46 (9)	1(1)	0	2(1)	52
Krajca-Radcliffe 1996	Richards I and II	16	0	15(1)	0	0	0	2
de Winter 2001	Richards II	26	2(2)	2	3	0	0	5
Kooijman 2003	Richards II	45	13(10)	3(3)	Unknown/nr (not reported)	1(1)	0	13(5)
Cartier 2005	Richards II	59	8(8)	5(5)	11* (6 poly wear, 2 snapping, 2 due to prosthesis edge projecting and 1 due to patellar subluxation- same pts as malposition/alignment)	0	0	0
Utukuri 2008	Richards II	20	0	0	0	0	0	0
van Jonbergen 2010	Richards II	181	84 (23) (additional 61 knees had changes in med comp.)	19(12)	0	4(4)	1(1)	66(5) (11 MUAs, 14 arthrot, 27 arthros, 10 other, 4 wear)
	TOTAL	432	107(43)	90(30)	15(1)	5(5)	3(2)	138(10)
Inlay, asymmetrical, non-anatomical								
Tauro 2001	Lubinus	76	7(5)	39(15)	0	0	0	14(1)
Smith	Lubinus	29	4(3)	6(3)	1(1)	0	0	0

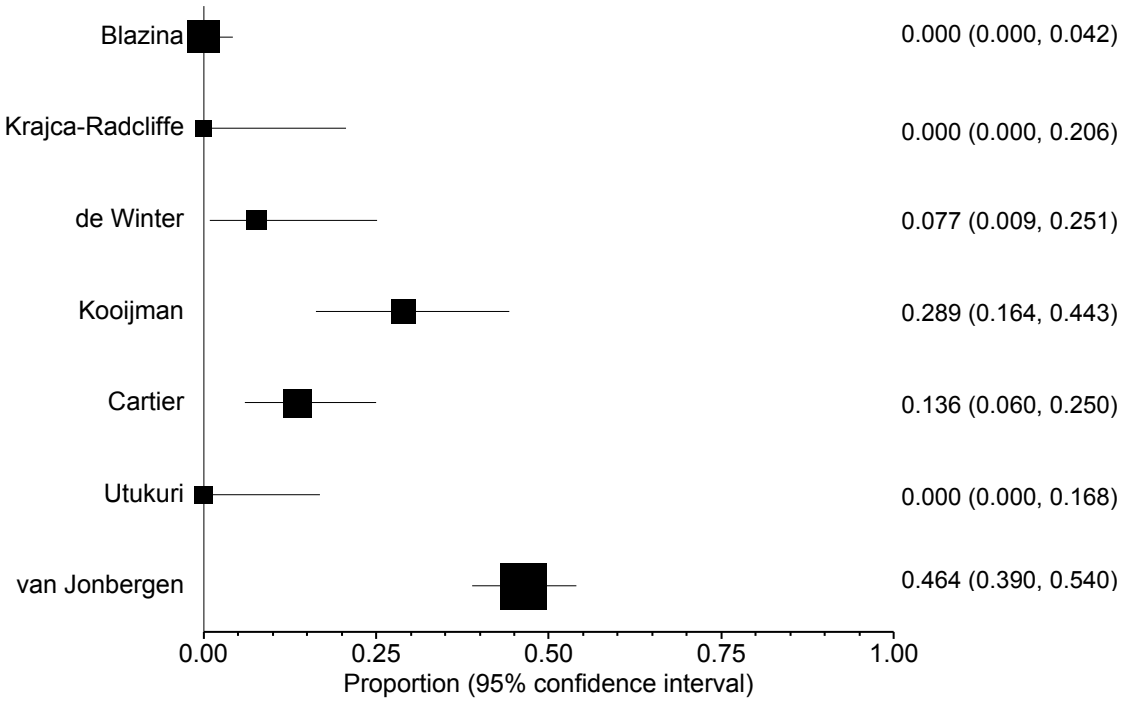
2002								
Board 2004	Lubinus	17	2(2)	5(2)	0	2	1(1)	2 (arthrosc)
Argenson 2005	Autocentric	57	14(14)	0	0	3(3)	3(3)	16(9)
Van Wagenberg 2009	Autocentric II	24	7(7)	7(4)	15	0	1	9
	TOTAL	203	34(31)	57(24)	16(1)	5(3)	4(4)	41(9)
Inlay, asymmetrical, anatomical								
Merchant 2005	LCS	16	0	0	0	0	0	0
Charalambous 2011	LCS	51	20(2*)	4	12(12*)	0	0	3(3)
	TOTAL	67	20(2)	4	12(12)	0	0	3(3)
Onlay, symmetrical, non-anatomical								
Nicol 2006	Avon	103	12(12)	1(1*)	1(1*)	0	0	1(1)
Ackroyd 2007	Avon	109	29(4)	1	0	0	0	6
Hollinghurst 2007	Avon	12	0	0	0	0	0	0
Leadbetter 2009	Avon	79	5(4)	1(1)	5	0	0	3(1)
Starks 2009	Avon	37	1	0	1(1)	0	0	1(1)
Odumenya 2010	Avon	50	14(3*)	1	2(2*) (same as TFOA pts)	0	0	0
Gao 2010	Avon	11	0	0	0	0	0	0
Sarda 2011	Avon	44	8(1)	8(1*)	4(1*)	0	0	2
Mont 2012	Avon	43	3(2*)	0	0	5(5*)	0	5
	TOTAL	488	72(26)	12(3)	13(5)	5(5)	0	18(3)
Onlay, asymmetrical, anatomical								

Hofmann 2009	Natural Knee II	40	0	0	0	0	0	4(2)
Monk 2012	FPV	15	0	0	0	0	0	0
Mofidi 2012	FPV	34	0	0	0	0	0	0
Williams 2013	FPV	53	4(4)	0	5(2)	0	1	4(1)
Beitzel 2013	Journey	22	0	0	0	0	0	0
	TOTAL	164	4(4)	0	5(2)	0	1	8(3)
Onlay, asymmetrical, patient-specific								
Butler 2009	Custom Performa Knee	22	0	0	0	0	0	8(1)
Sisto 2010	Kinematch	25	0	0	0	0	0	0
	TOTAL	47	0	0	0	0	0	8(1)
Mixed Group								
Arciero 1988	Richards and CSF-Wright	25	3(3)	5(2)	1	0	0	6
Arnbjornsson 1998	Richards I and II Lubinus Miscellaneous other	113	4	12	15(10)	0	3	27
Mohammed 2008	Lubinus Avon FPV	101	3(3)	8	18	0	1(1)	4
	TOTAL	239	10(6)	25(2)	34(10)	0	4(1)	37
Total Knee Replacement								
Meding 2007	AGC Legacy	33	0	0	0	0	0	0
Laskin	Genesis	48	0	10	3	0	0	0

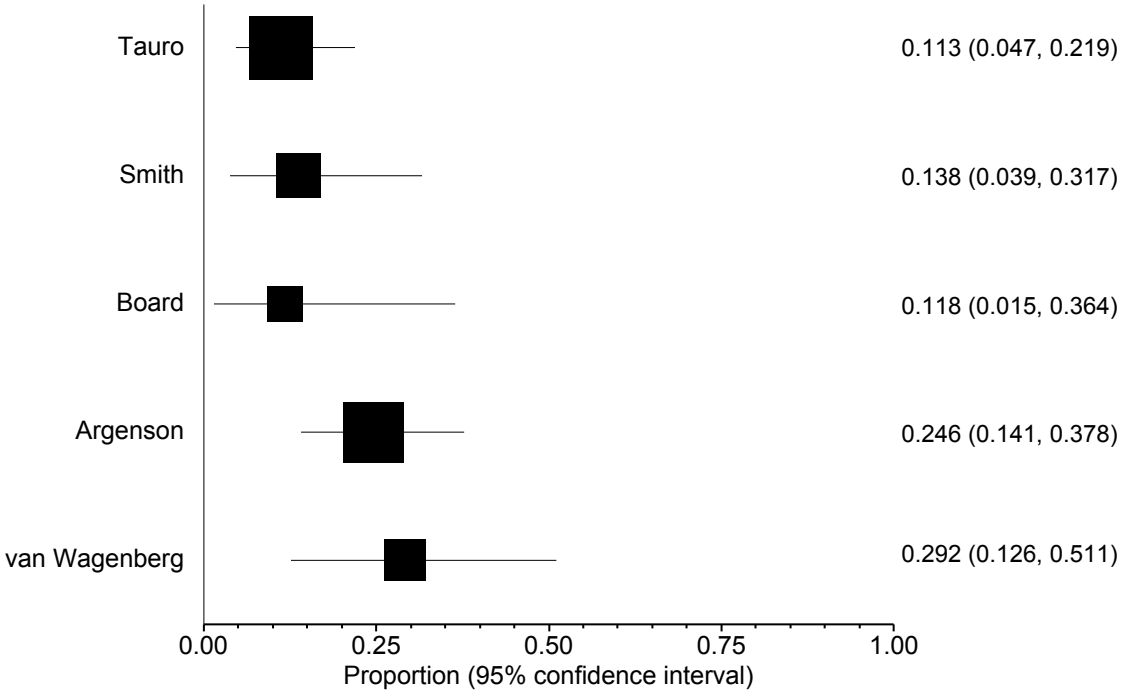
1999								
Thompson 2001	LCS	33	0	0	0	0	2	2
Mont 2002	Porous Coated Anatomic Duracon Insall-Burstein II	30	0	0	0	0	0	0
Dalury 2005	Press Fit Condylar	33	0	4	0	0	0	0
Parvizi 2001	Press Fit Condylar Genesis Total Condylar	31	0	7*(1)	6*(1) same pt as misalignment	1	0	5
	TOTAL	208	0	21(1)	9(1)	1	2	7
Comparison								
Dahm 2010	Avon	23	0	0	0	0	0	0
Dahm 2010	Zimmer SIGMA	22	0	0	0	0	0	2
	TOTAL	45	0	0	0	0	0	2

*knees with dual pathology
(x) numbers in brackets represent the number that underwent revision surgery

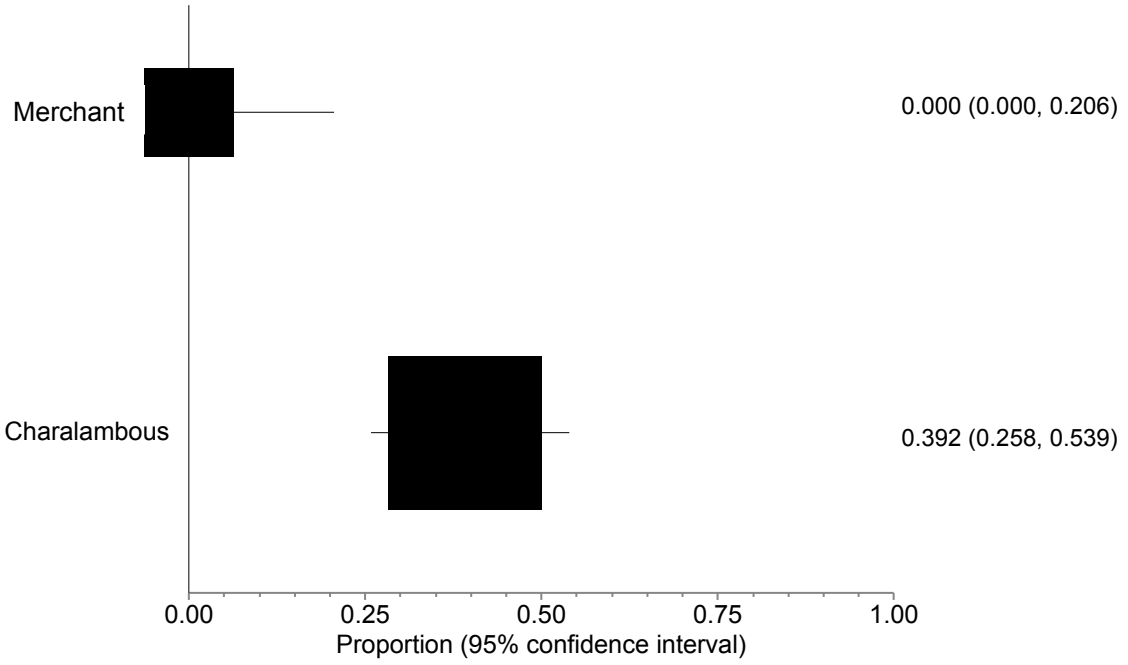
ISN Disease Progression



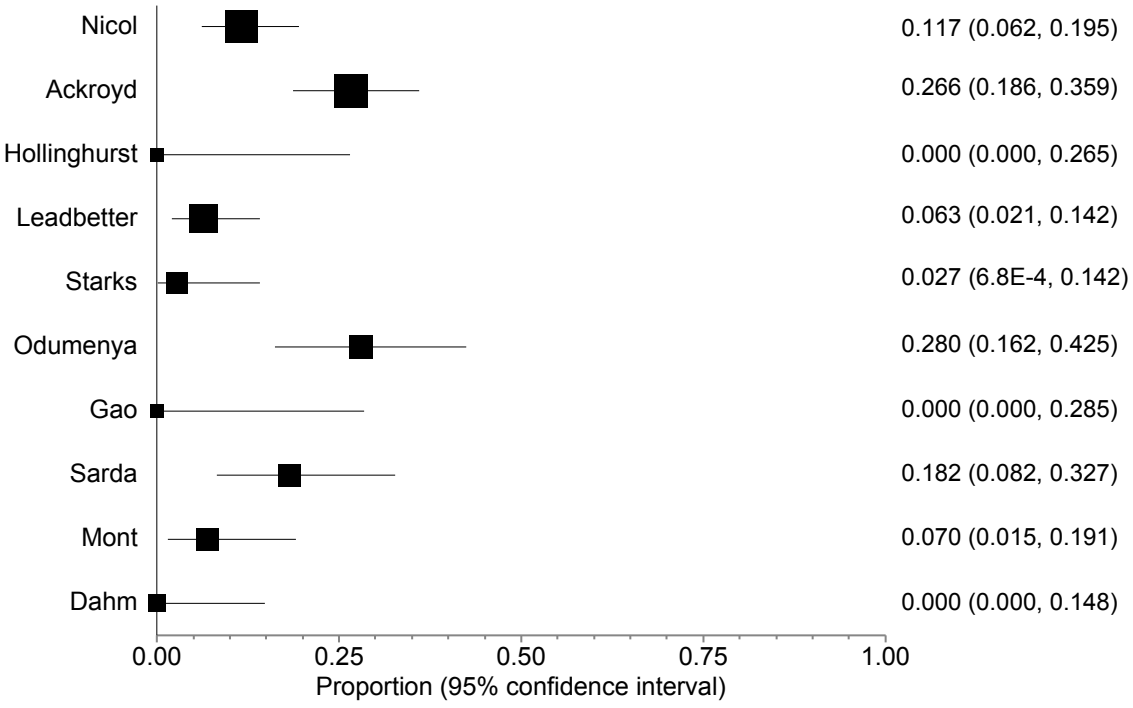
IAN Disease Progression



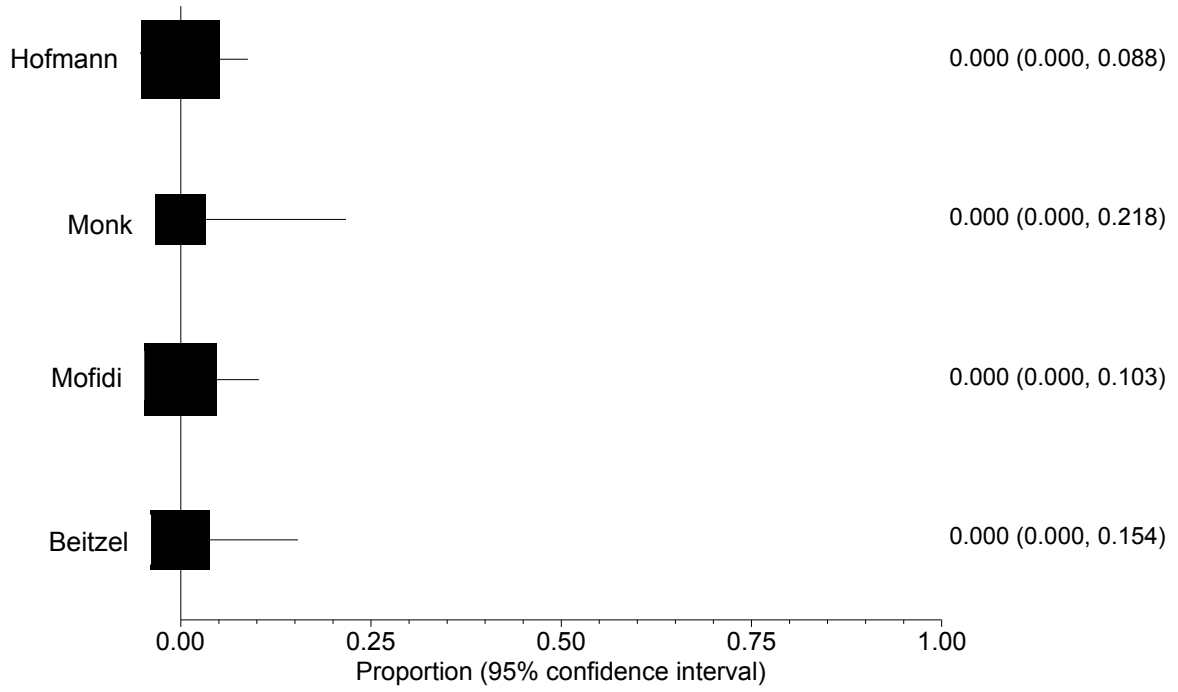
IAA Disease Progression



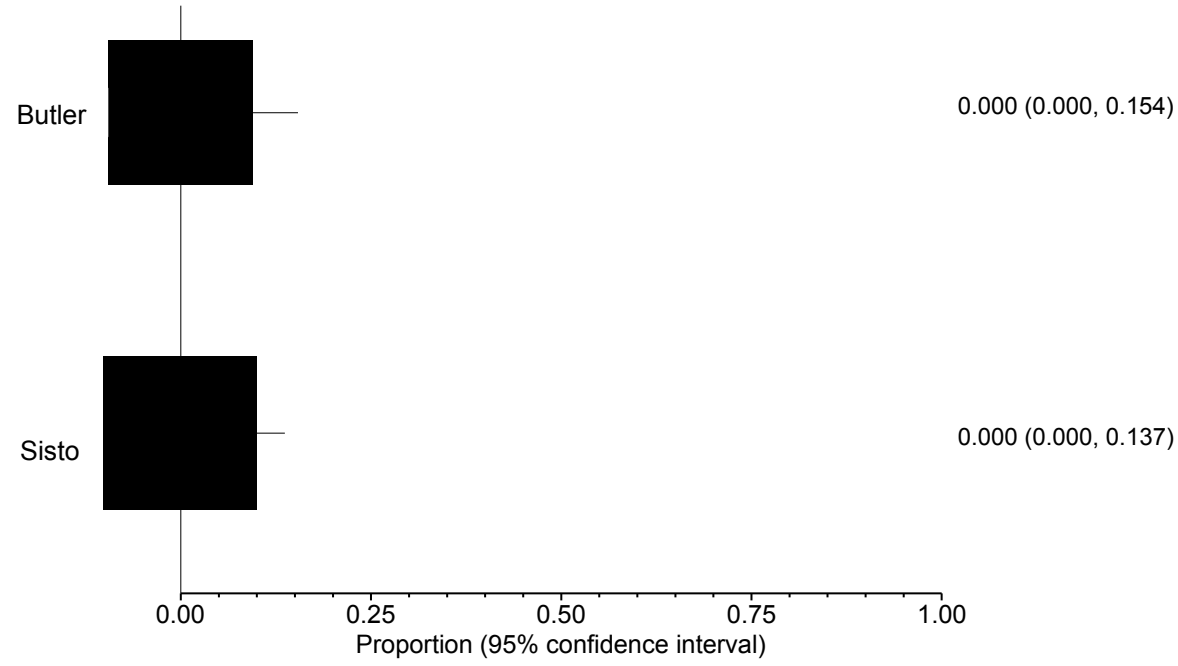
OSN Disease Progression



OAA Disease Progression



OAP Disease Progression



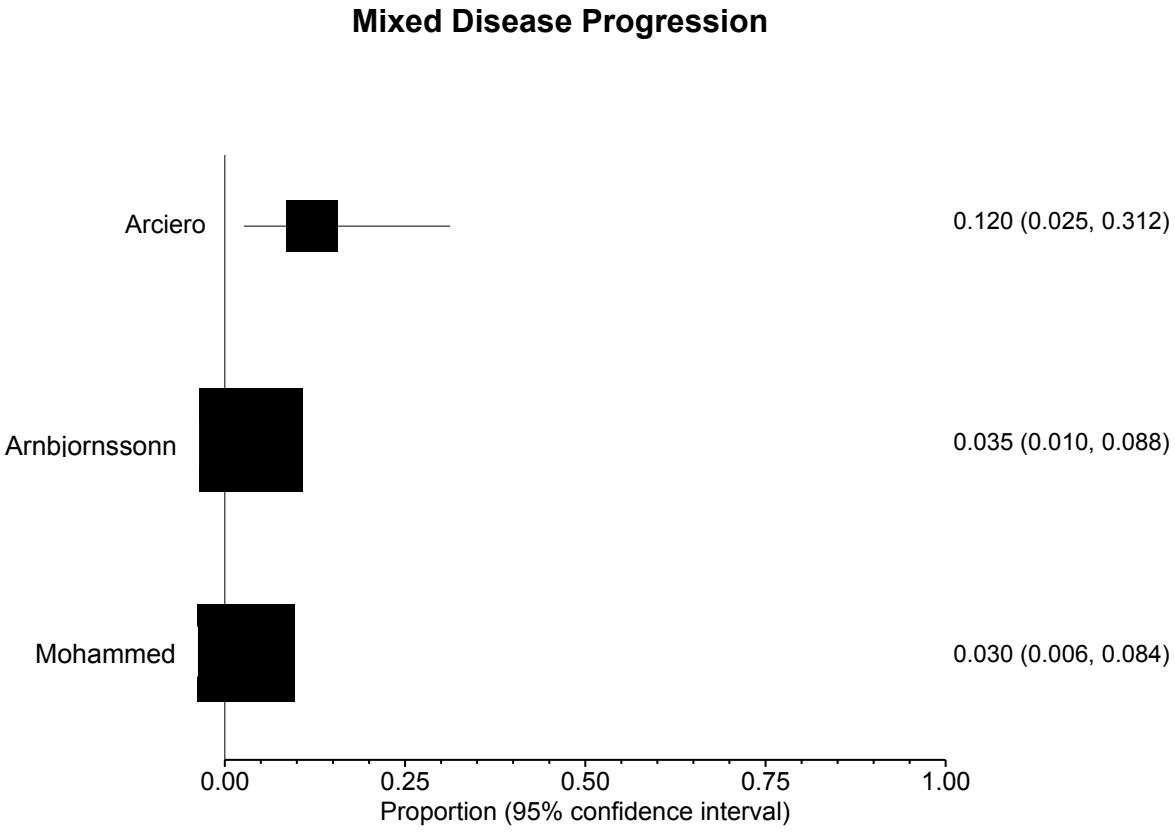


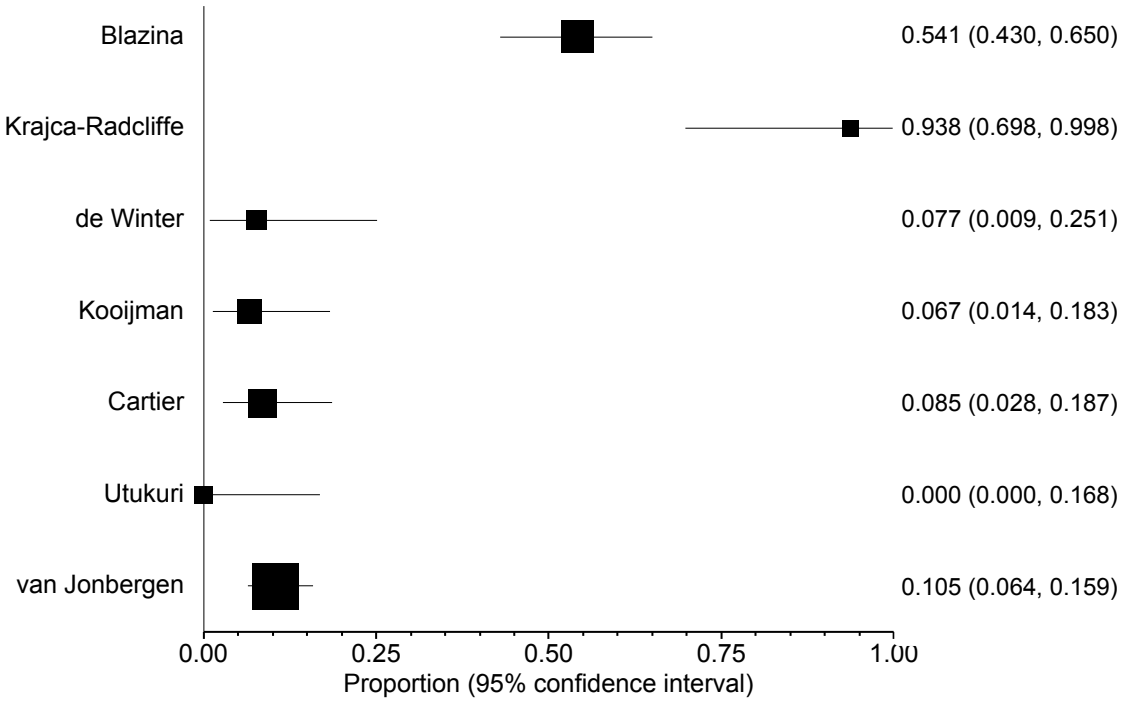
Figure 3-5 **Proportion of Disease Progression**

Table 3-9 Proportion of Disease Progression

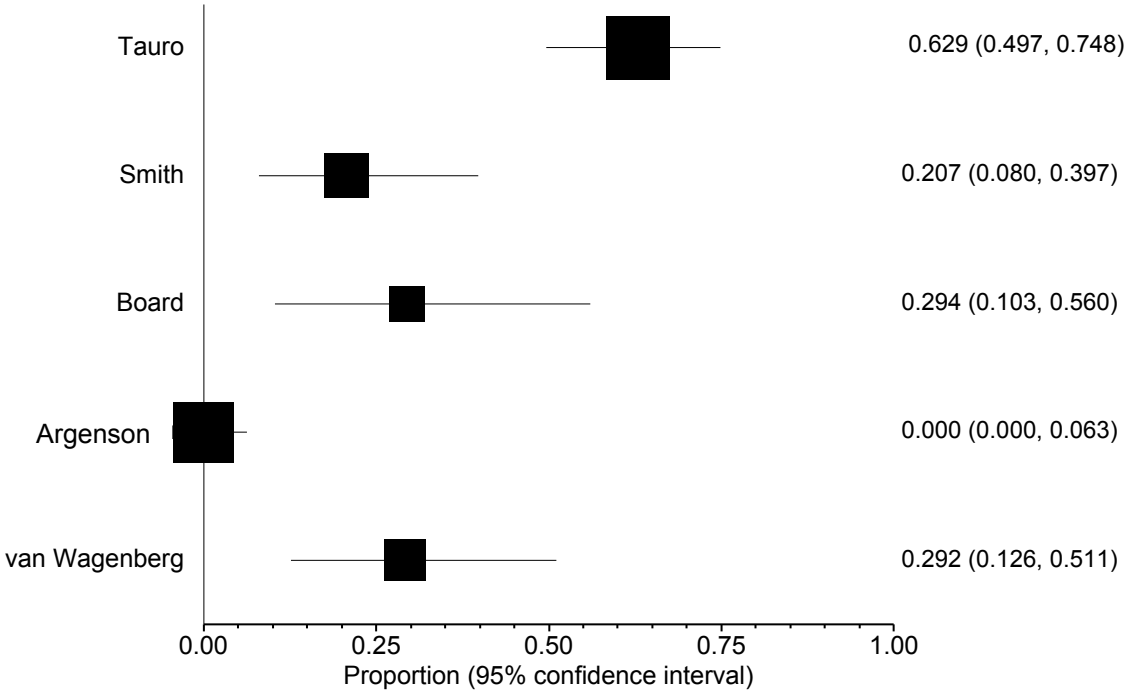
Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0	0	0.04	19.59
Krajca-Radcliffe 1996	0	0	0.21	3.87
de Winter 2001	0.08	0.01	0.25	6.15
Kooijman 2003	0.29	0.16	0.44	10.48
Cartier 2005	0.14	0.06	0.25	13.67
Utukuri 2008	0	0	0.17	4.78
van Jonbergen 2010	0.46	0.39	0.54	41.46
IAN				
Tauro 2001	0.11	0.05	0.22	32.47
Smith 2002	0.14	0.04	0.32	15.46
Board 2004	0.12	0.01	0.36	9.28
Argenson 2005	0.25	0.14	0.38	29.90
van Wagenberg 2009	0.29	0.13	0.51	12.89
IAA				
Merchant 2005	0	0	0.21	24.64
Charalambous 2011	0.39	0.26	0.54	75.36
OSN				
Nicol 2006	0.12	0.06	0.19	19.96
Ackroyd 2007	0.27	0.19	0.36	21.11
Hollinghurst 2007	0	0	0.26	2.50
Leadbetter 2009	0.06	0.02	0.14	15.36
Starks 2009	0.03	0	0.14	7.29
Odumenya 2010	0.28	0.16	0.42	9.79
Gao 2010	0	0	0.28	2.30
Sarda 2011	0.18	0.08	0.33	8.64
Mont 2012	0.07	0.01	0.19	8.44
Dahm 2010	0	0	0.15	4.61
OAA				
Hofmann 2009	0	0	0.09	35.65
Monk 2012	0	0	0.22	13.91
Mofidi 2012	0	0	0.10	30.43
Beitzel 2013	0	0	0.15	20.01
OAP				
Butler 2009	0	0	0.15	46.94
Sisto 2010	0	0	0.14	53.06
Mixed				
Arciero 1988	0.12	0.03	0.31	10.74
Arnbjornsson 1998	0.04	0.01	0.09	47.11
Mohammed 2008	0.03	0.01	0.08	42.15

*number of knees with disease progression divided by the total number of knees assessed

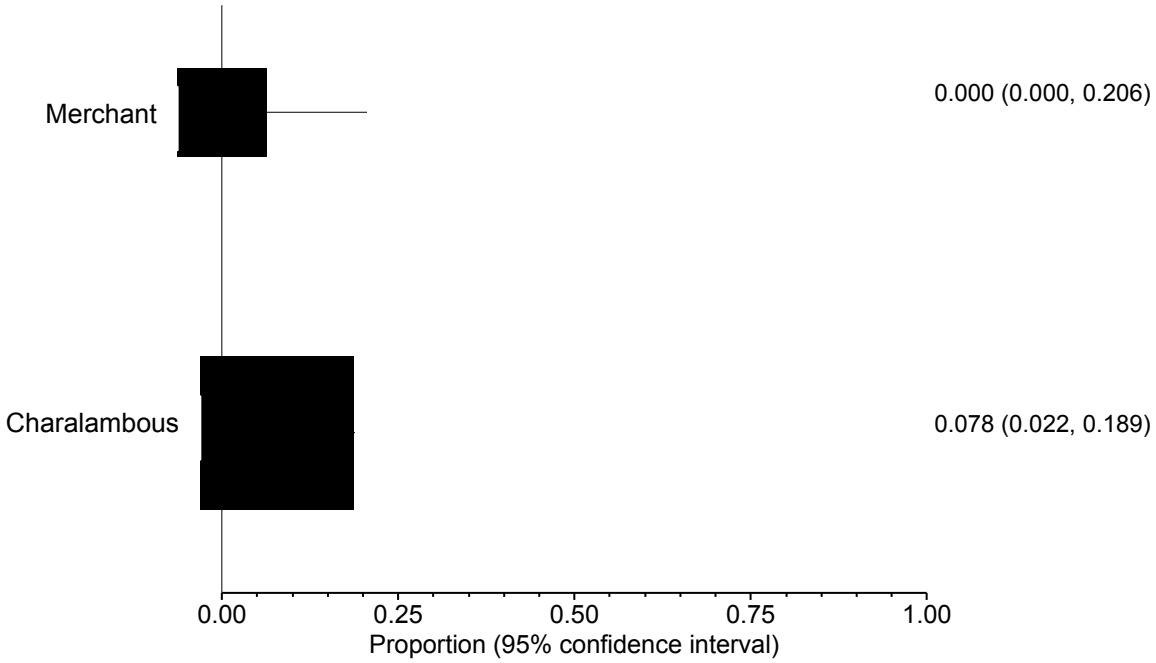
ISN Malpositioning



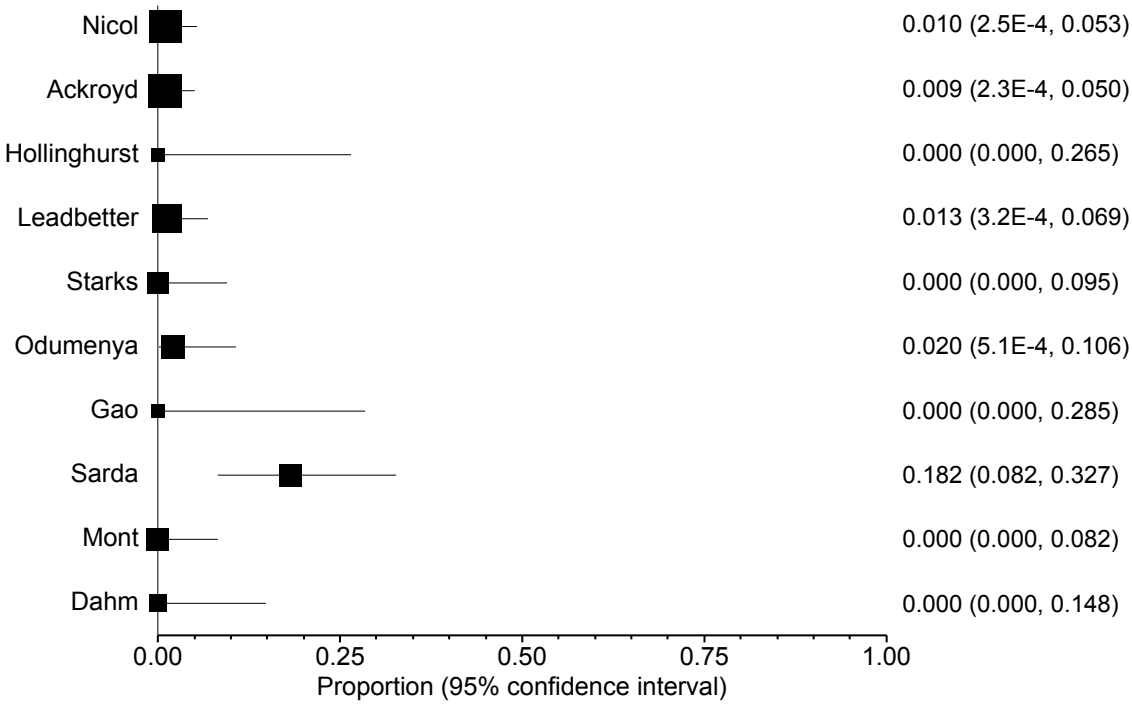
IAN Malpositioning



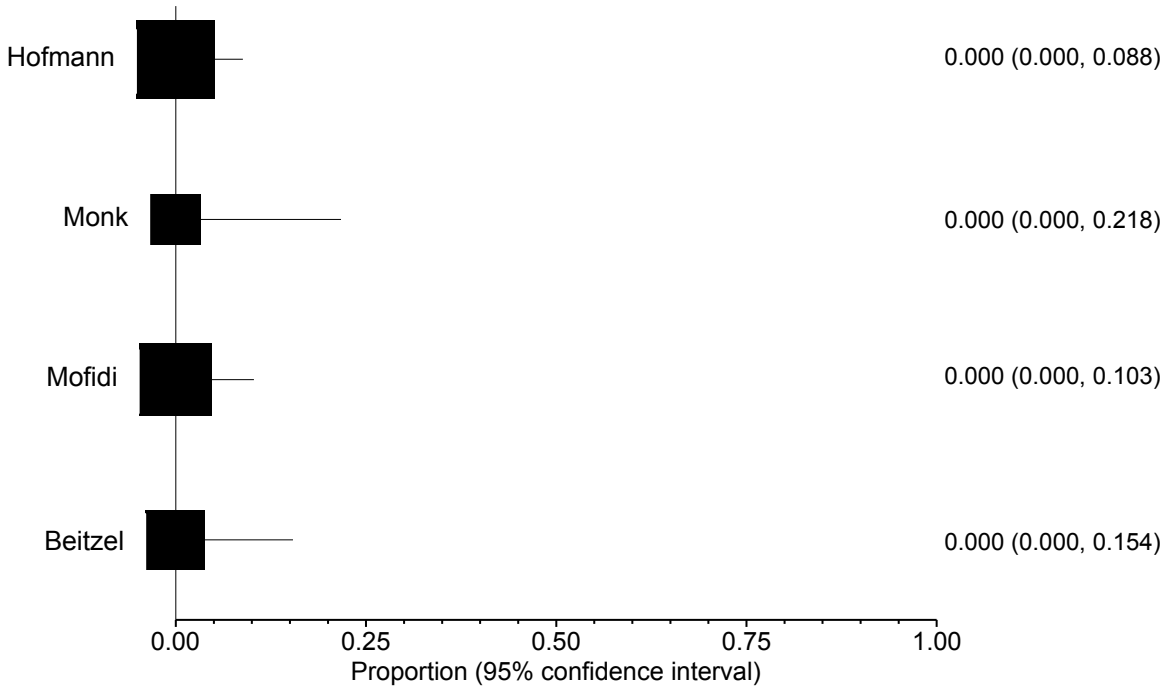
IAA Malpositioning



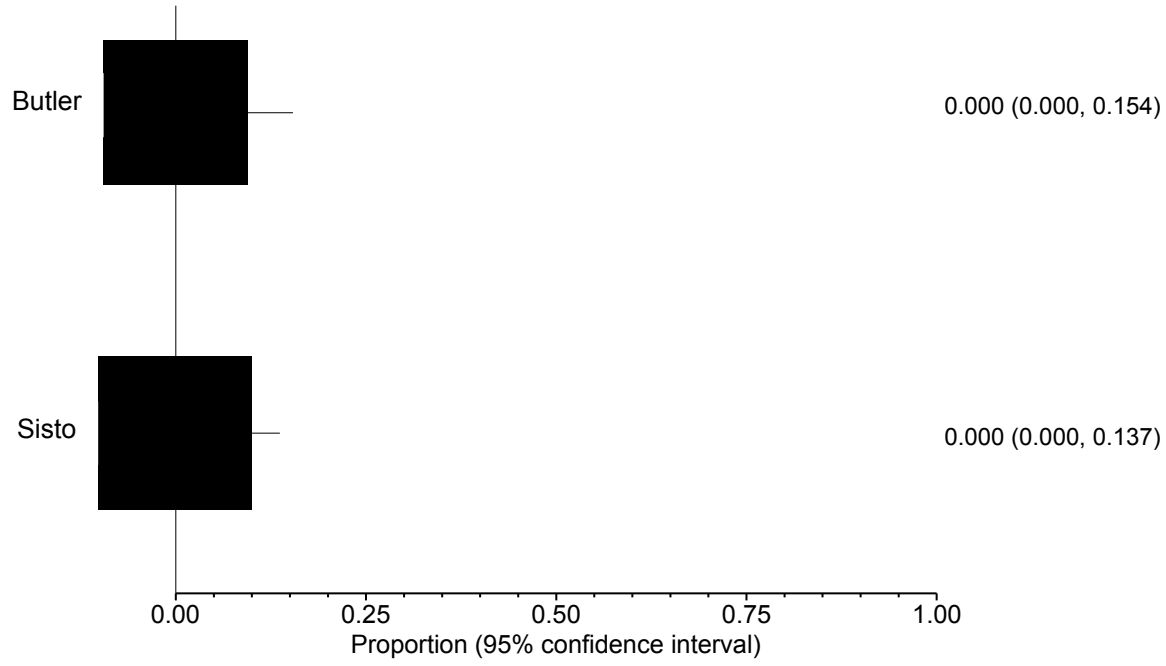
OSN Malpositioning



OAA Malpositioning



OAP Malpositioning



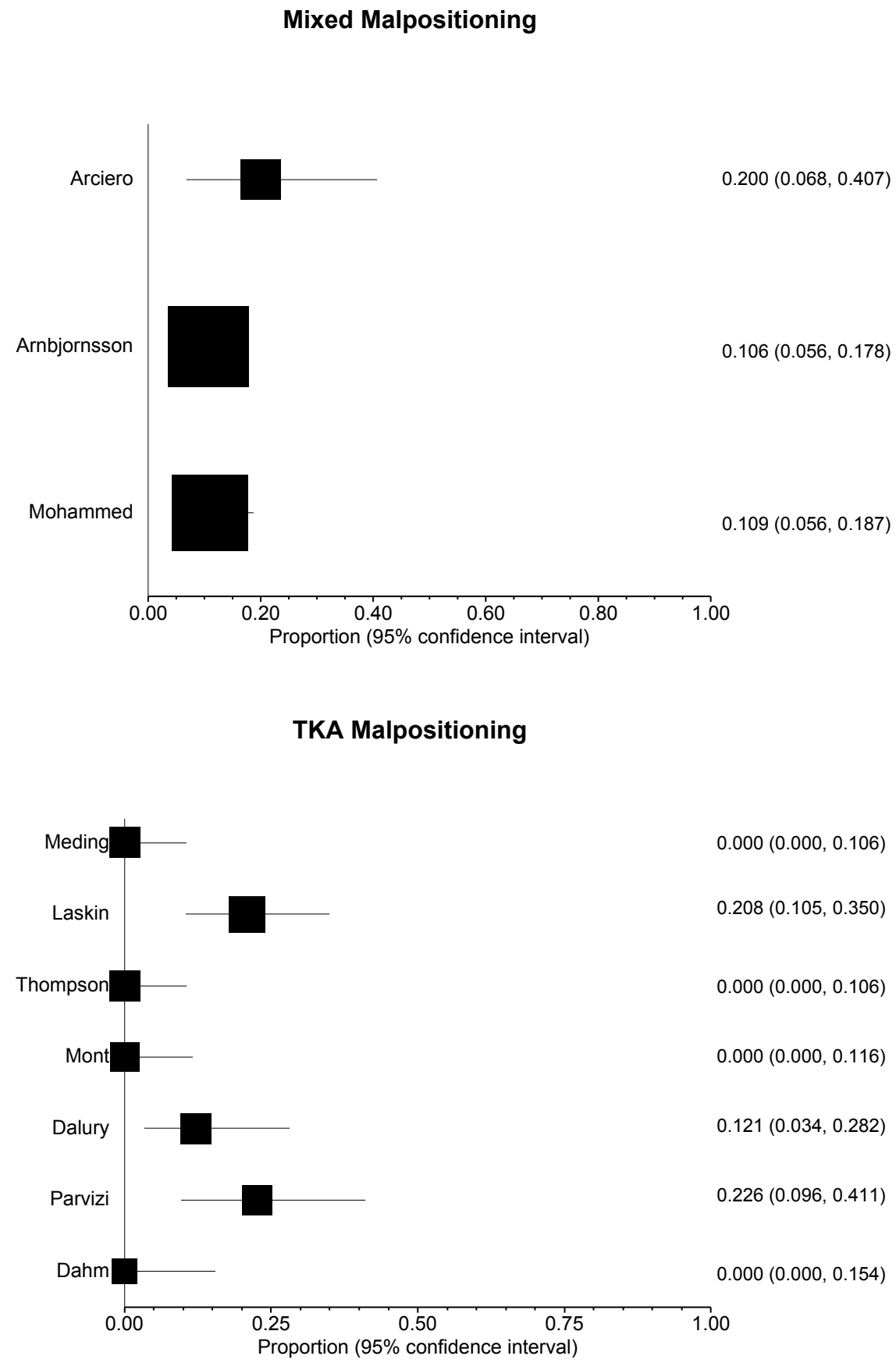


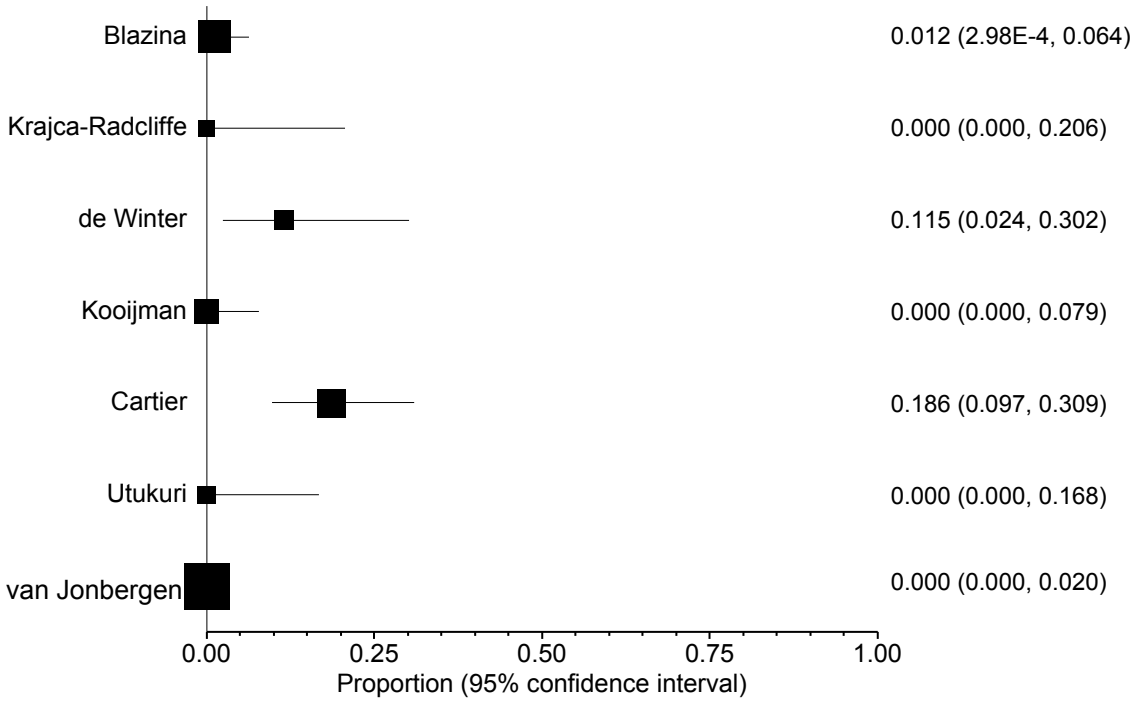
Figure 3-6 **Proportion of Malpositioning**

Table 3-10 Proportion of Malpositioning

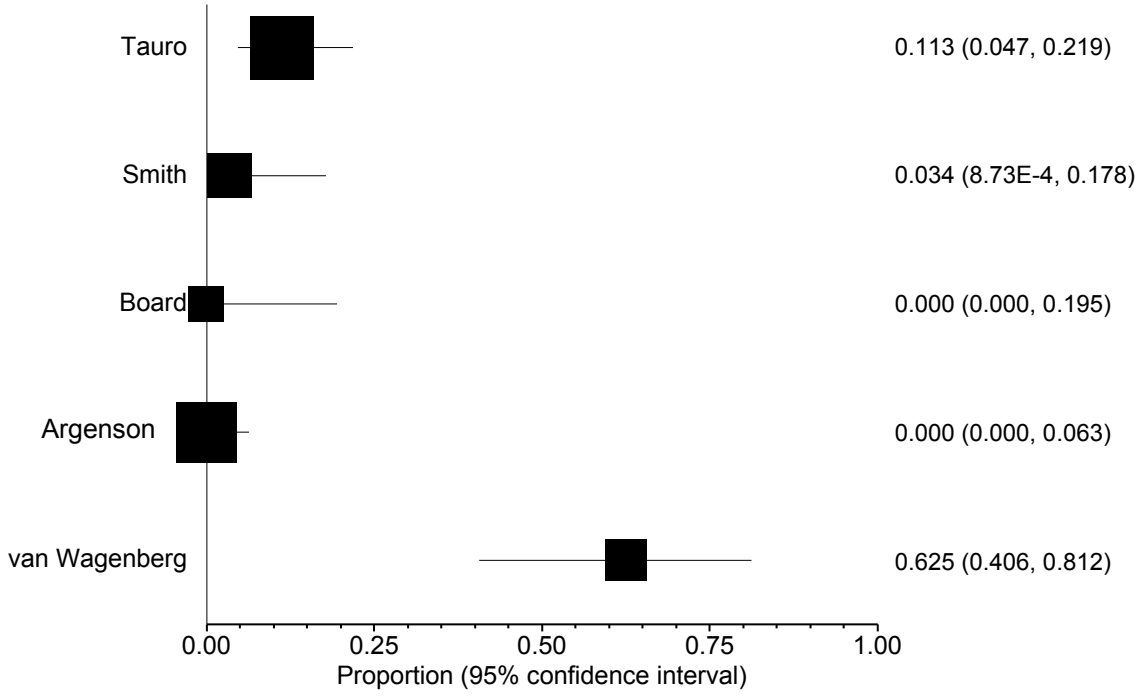
Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0.54	0.43	0.65	19.59
Krajca-Radcliffe 1996	0.94	0.70	1	3.87
de Winter 2001	0.08	0.01	0.25	6.15
Kooijman 2003	0.07	0.01	0.18	10.48
Cartier 2005	0.08	0.03	0.19	13.67
Utukuri 2008	0	0	0.17	4.78
van Jonbergen 2010	0.10	0.06	0.16	41.46
IAN				
Tauro 2001	0.63	0.50	0.75	32.47
Smith 2002	0.21	0.08	0.40	15.46
Board 2004	0.29	0.10	0.56	9.28
Argenson 2005	0	0	0.06	29.90
van Wagenberg 2009	0.29	0.13	0.51	12.87
IAA				
Merchant 2005	0	0	0.21	24.64
Charalambous 2011	0.08	0.02	0.19	75.36
OSN				
Nicol 2006	0.01	0	0.05	19.96
Ackroyd 2007	0.01	0	0.05	21.11
Hollinghurst 2007	0	0	0.26	2.50
Leadbetter 2009	0.01	0	0.07	15.36
Starks 2009	0	0	0.09	7.29
Odumenya 2010	0.02	0	0.11	9.79
Gao 2010	0	0	0.28	2.30
Sarda 2011	0.18	0.08	0.33	8.64
Mont 2012	0	0	0.082	8.45
Dahm 2010	0	0	0.15	4.61
OAA				
Hofmann 2009	0	0	0.09	35.65
Monk 2012	0	0	0.22	13.91
Mofidi 2012	0	0	0.10	30.43
Beitzel 2013	0	0	0.15	20.01
OAP				
Butler 2009	0	0	0.15	46.94
Sisto 2010	0	0	0.14	53.06
Mixed				
Arciero 1988	0.2	0.07	0.41	10.74
Arnbjornsson 1998	0.11	0.06	0.18	47.11
Mohammed 2008	0.11	0.06	0.19	42.15
TKA				
Meding 2007	0	0	0.11	14.35
Laskin 1999	0.21	0.10	0.35	20.68
Thompson 2001	0	0	0.11	14.35
Mont 2002	0	0	0.12	13.08
Dalury 2005	0.12	0.03	0.28	14.35
Parvizi 2001	0.23	0.10	0.41	13.50
Dahm 2010	0	0	0.15	9.70

*number of knees with malpositioning divided by the total number of knees assessed

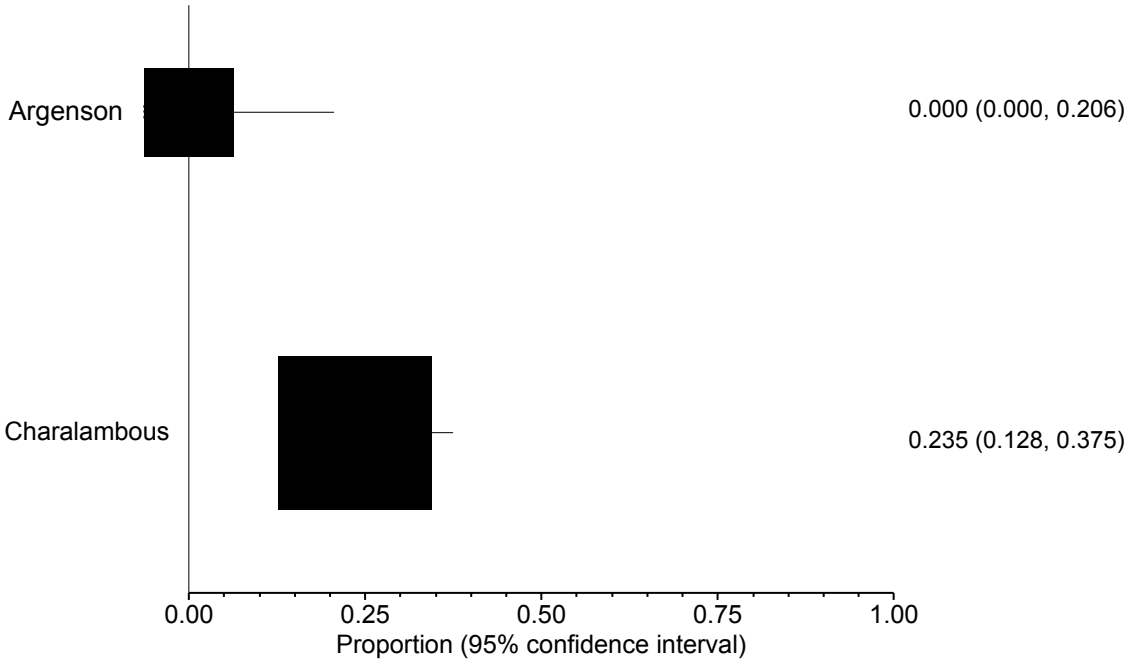
ISN Persistent Pain



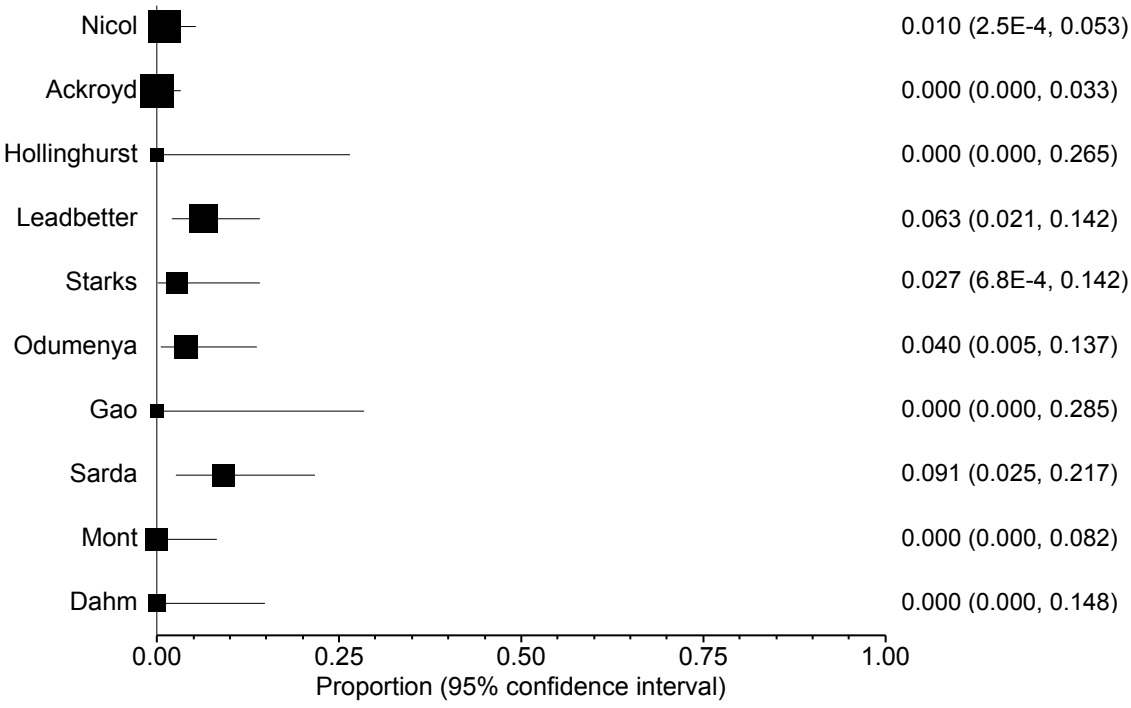
IAN Persistent Pain



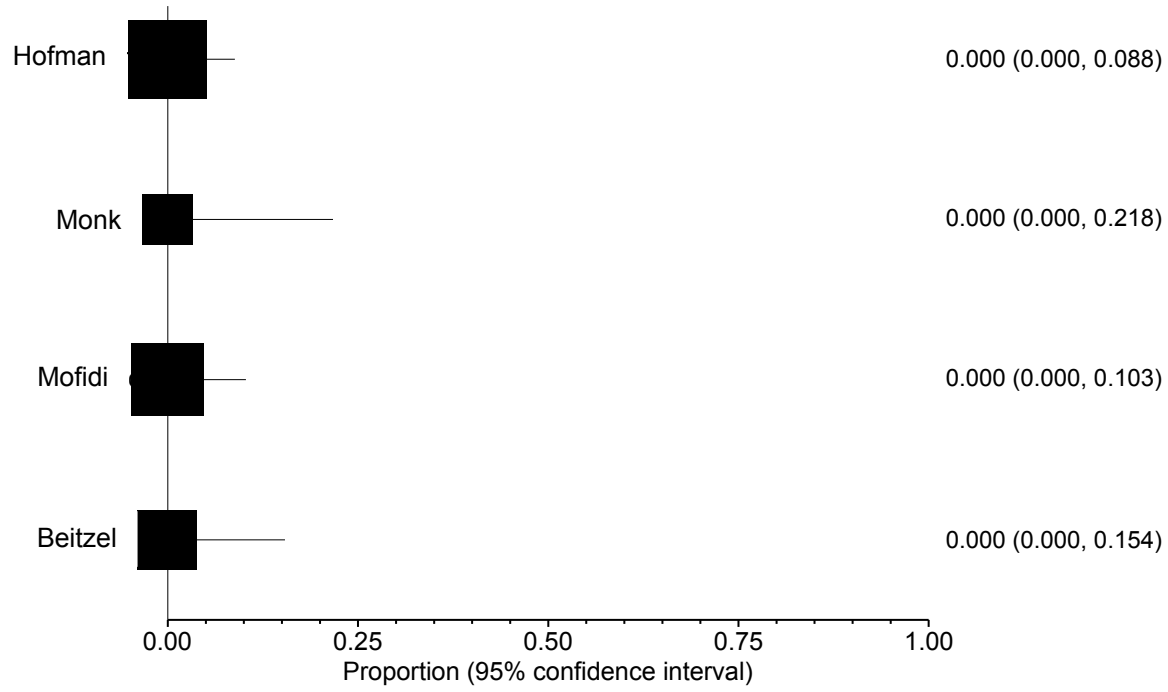
IAA Persistent Pain



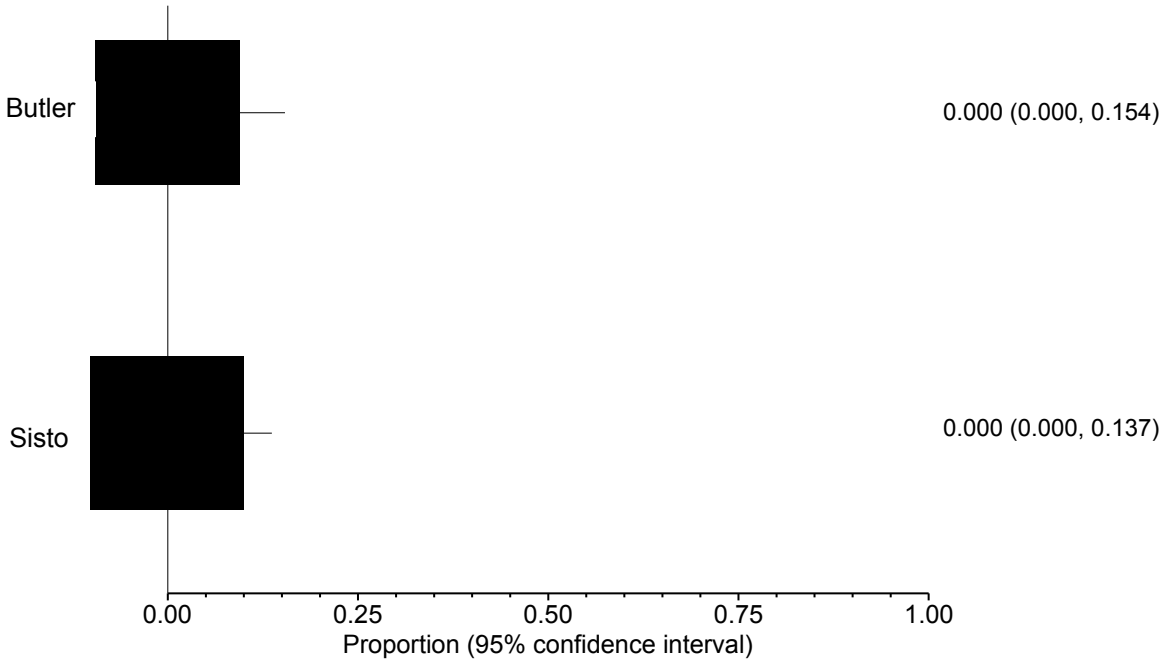
OSN Persistent Pain

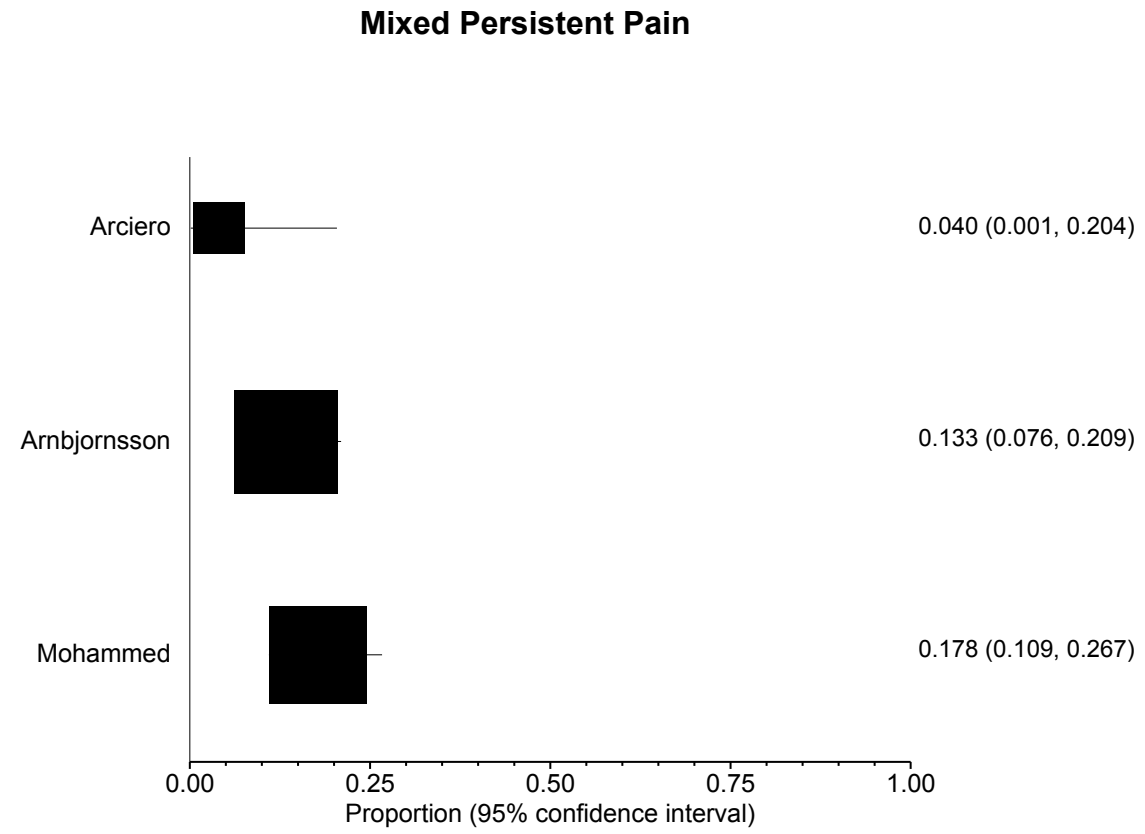


OAA Persistent Pain



OAP Persistent Pain





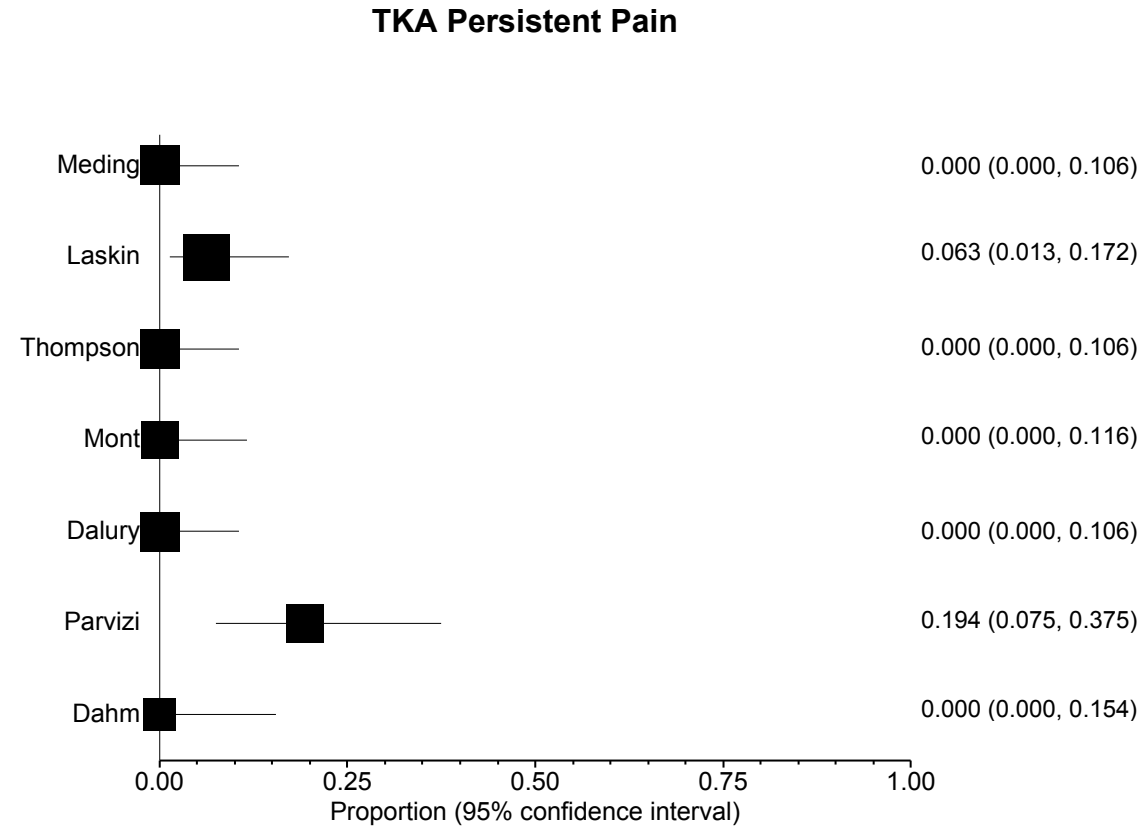


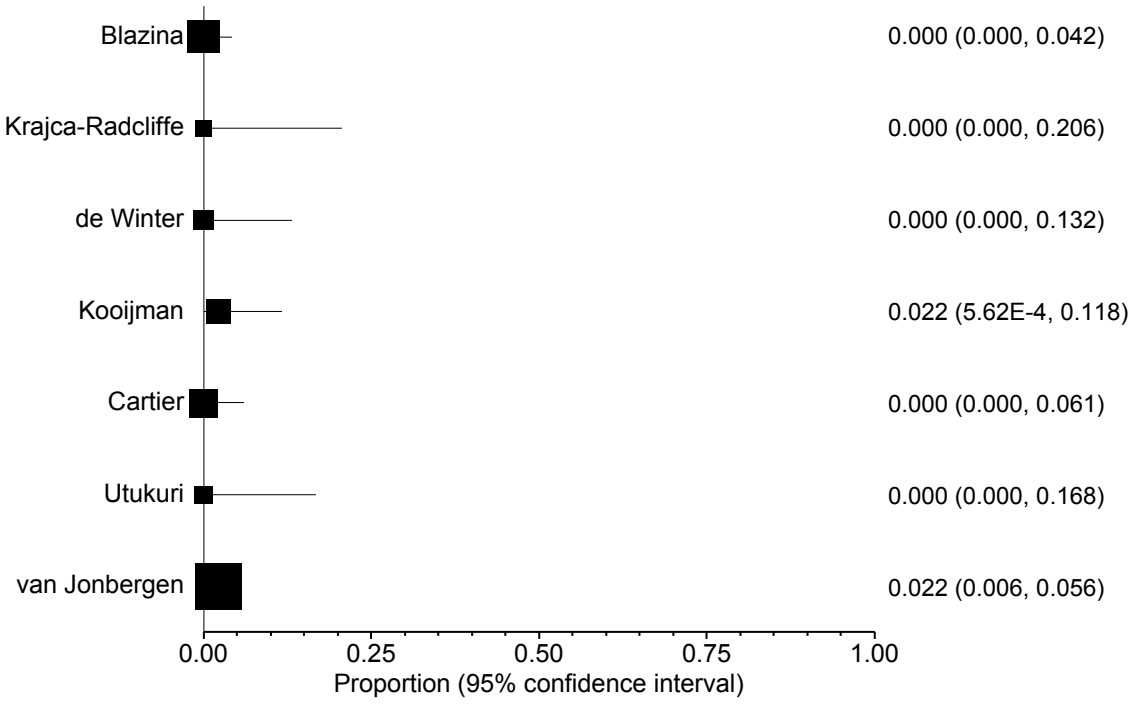
Figure 3-7 **Proportion of Persistent Pain**

Table 3-11 Proportion of Persistent Pain

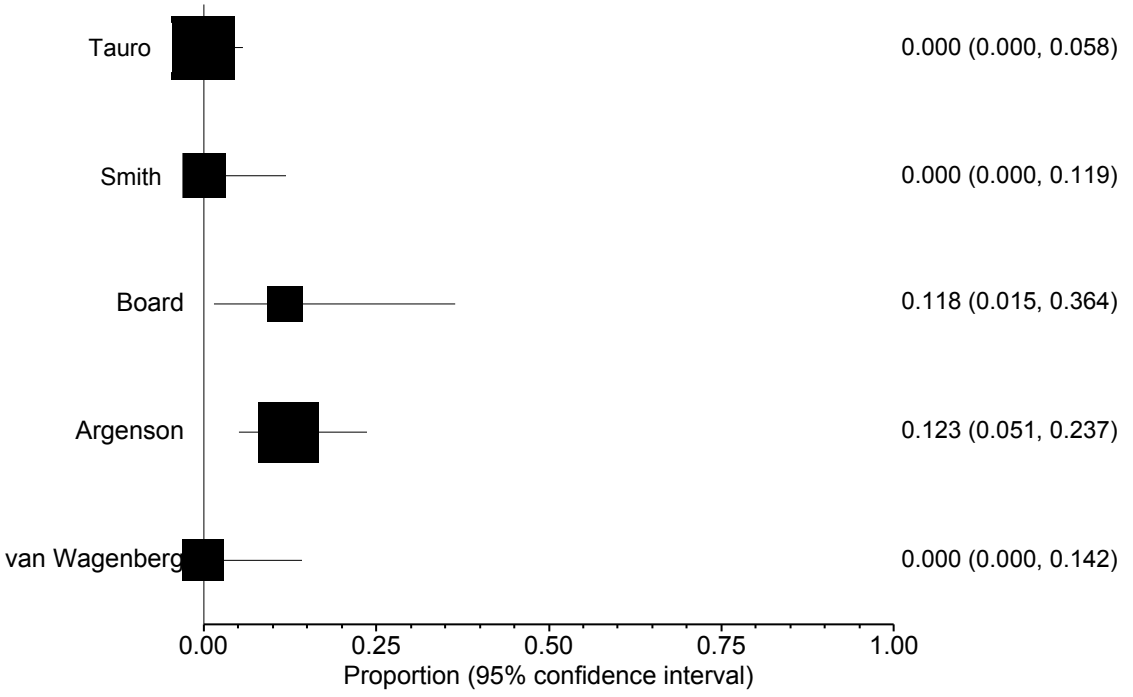
Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0.012	0	0.06	19.59
Krajca-Radcliffe 1996	0	0	0.21	3.87
de Winter 2001	0.12	0.02	0.30	6.15
Kooijman 2003	0	0	0.08	10.48
Cartier 2005	0.19	0.097	0.31	13.67
Utukuri 2008	0	0	0.17	4.78
van Jonbergen 2010	0	0	0.02	41.46
IAN				
Tauro 2001	0.12	0.05	0.22	32.47
Smith 2002	0.034	0	0.18	15.46
Board 2004	0	0	0.20	9.28
Argenson 2005	0	0	0.06	29.90
van Wagenberg 2009	0.63	0.41	0.81	12.89
IAA				
Merchant 2005	0	0	0.21	24.64
Charalambous 2011	0.24	0.13	0.37	75.36
OSN				
Nicol 2006	0.01	0	0.05	19.96
Ackroyd 2007	0	0	0.03	21.11
Hollinghurst 2007	0	0	0.26	2.50
Leadbetter 2009	0.06	0.02	0.14	15.36
Starks 2009	0.03	0	0.14	7.29
Odumenya 2010	0.04	0	0.14	9.79
Gao 2010	0	0	0.28	2.30
Sarda 2011	0.09	0.03	0.22	8.63
Mont 2012	0	0	0.08	8.45
Dahm 2010	0	0	0.15	4.61
OAA				
Hofmann 2009	0	0	0.09	35.65
Monk 2012	0	0	0.22	13.91
Mofidi 2012	0	0	0.10	30.43
Beitzel 2013	0	0	0.15	20.01
OAP				
Butler 2009	0	0	0.15	46.94
Sisto 2010	0	0	0.14	53.06
Mixed				
Arciero 1988	0.04	0	0.20	10.74
Arnbjornsson 1998	0.13	0.08	0.21	47.11
Mohammed 2008	0.18	0.11	0.27	42.15
TKA				
Meding 2007	0	0	0.11	14.35
Laskin 1999	0.06	0.01	0.17	20.68
Thompson 2001	0	0	0.11	14.35
Mont 2002	0	0	0.12	13.08
Dalury 2005	0	0	0.11	14.35
Parvizi 2001	0.19	0.07	0.37	13.50
Dahm 2010	0	0	0.15	9.70

*number of knees with persistent pain divided by the total number of knees assessed

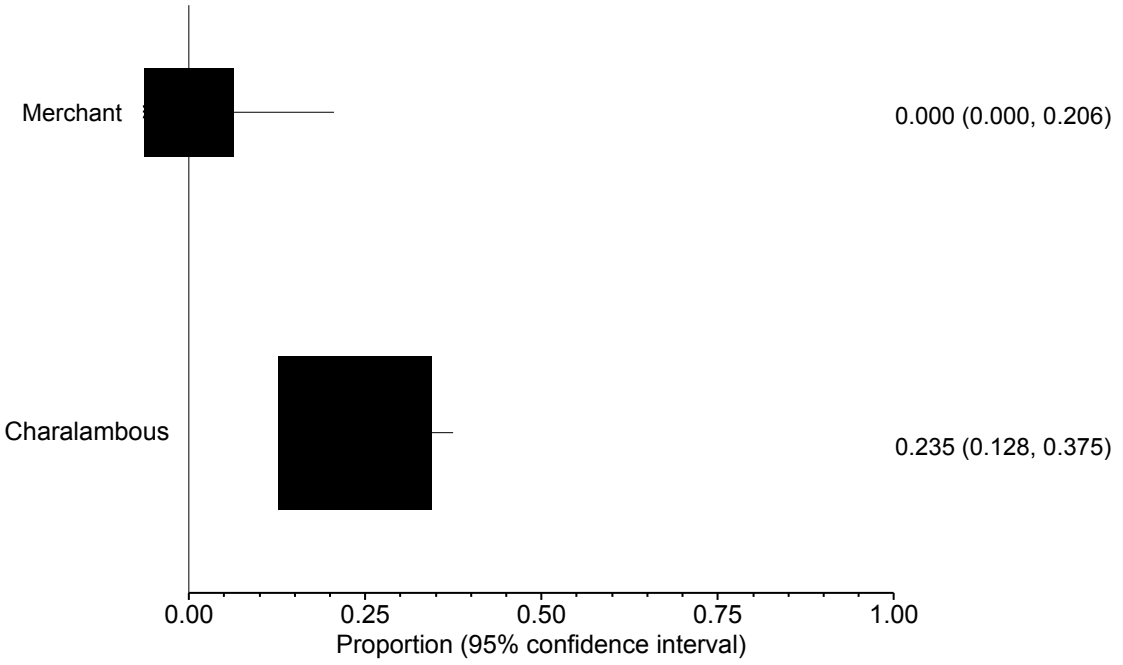
ISN Aseptic Loosening



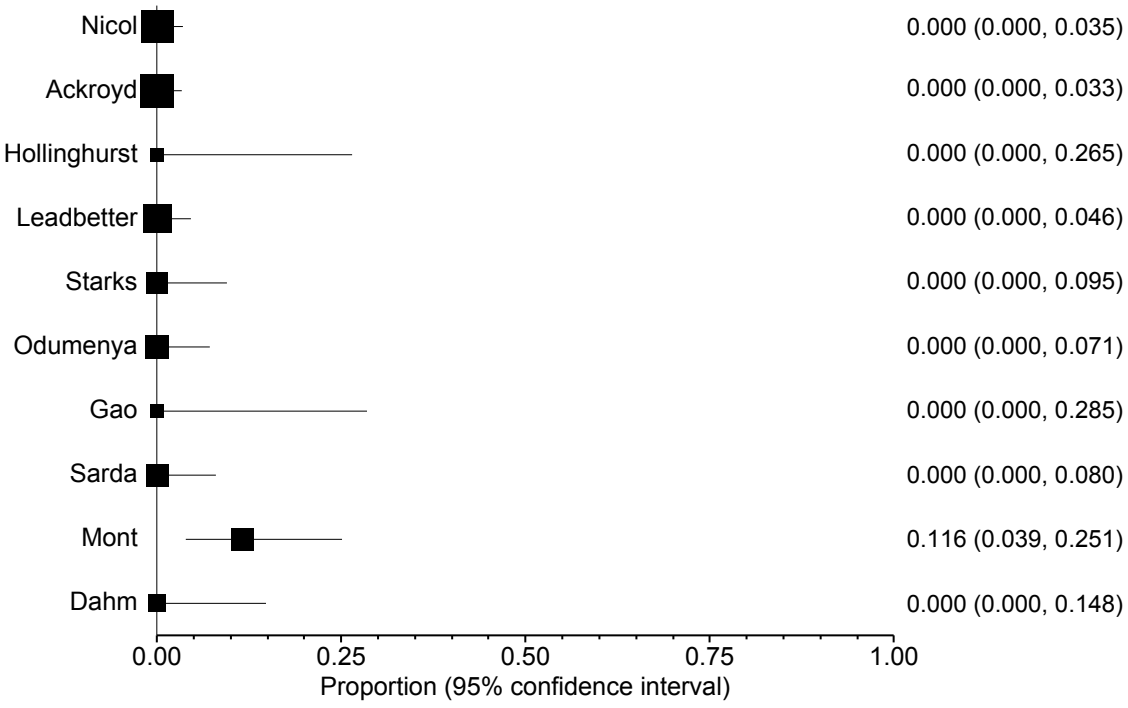
IAN Aseptic Loosening



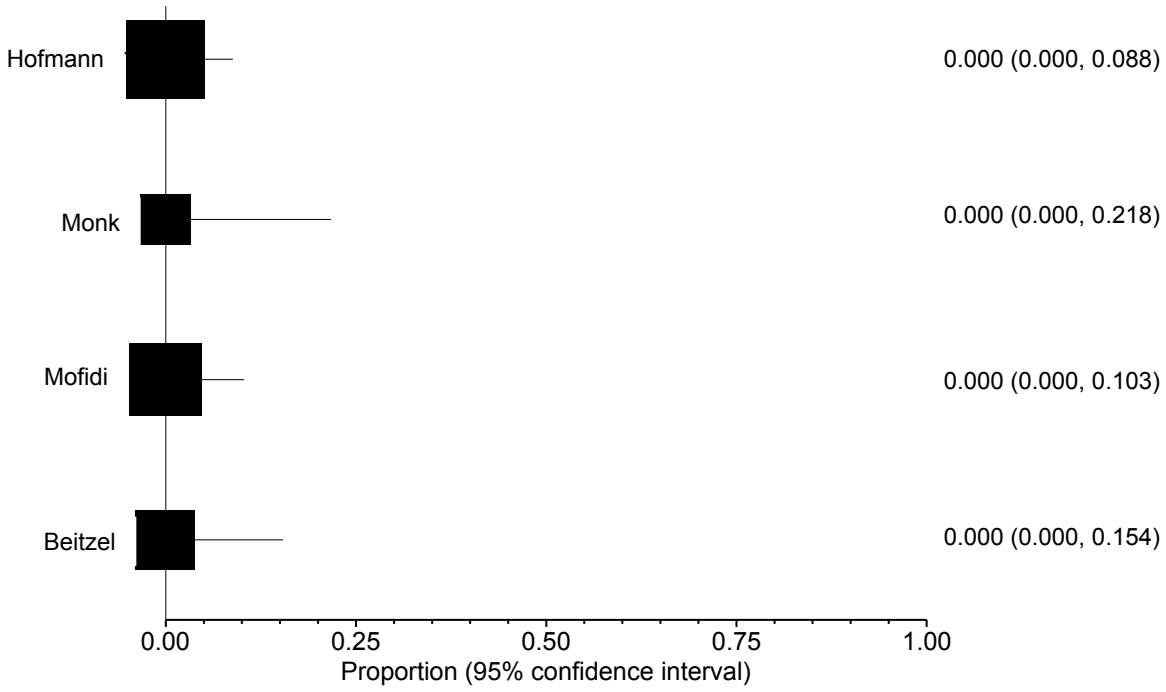
IAA Aseptic Loosening



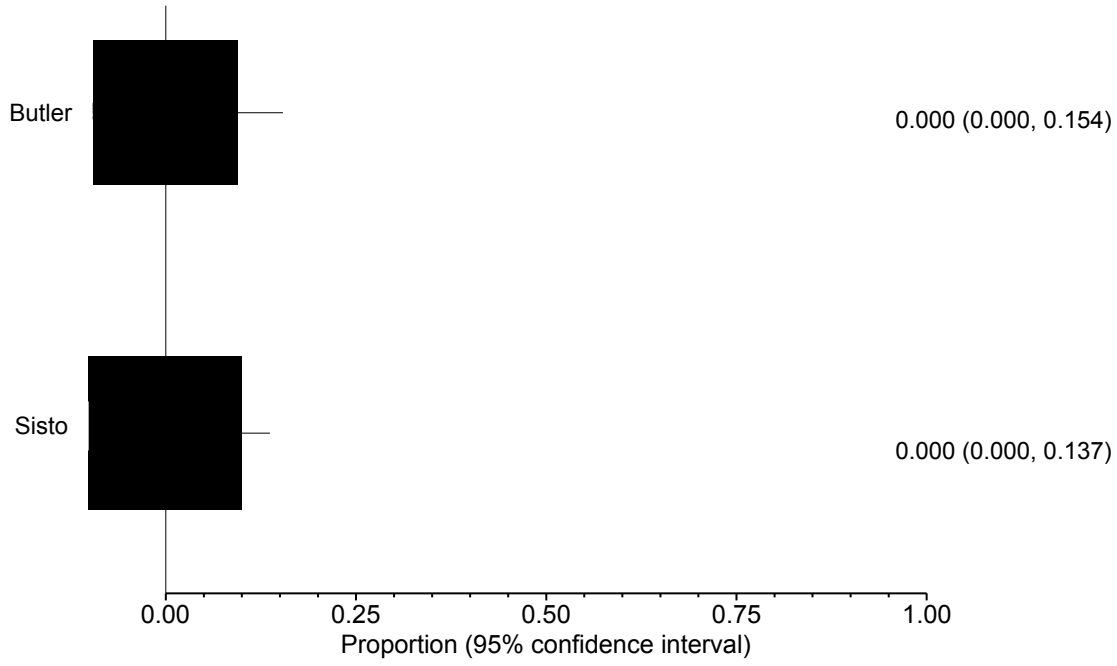
OSN Aseptic Loosening

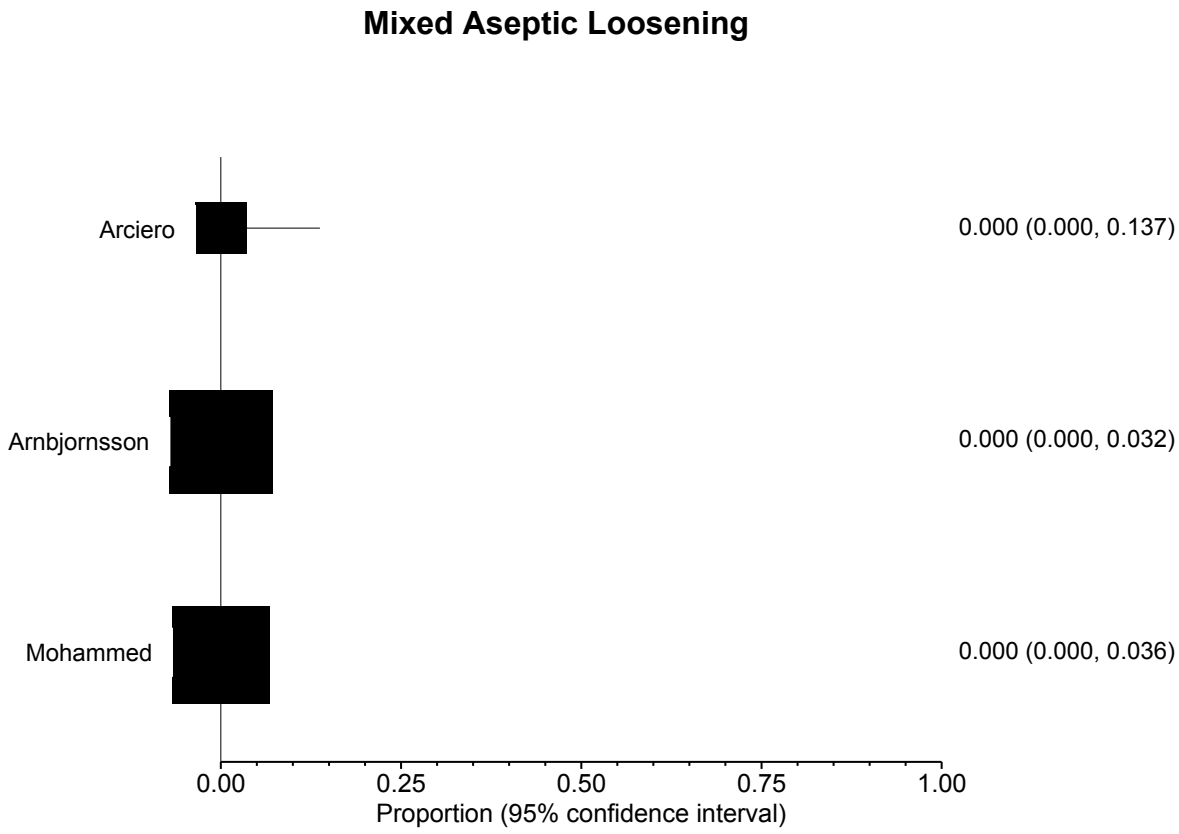


OAA Aseptic Loosening



OAP Aseptic Loosening





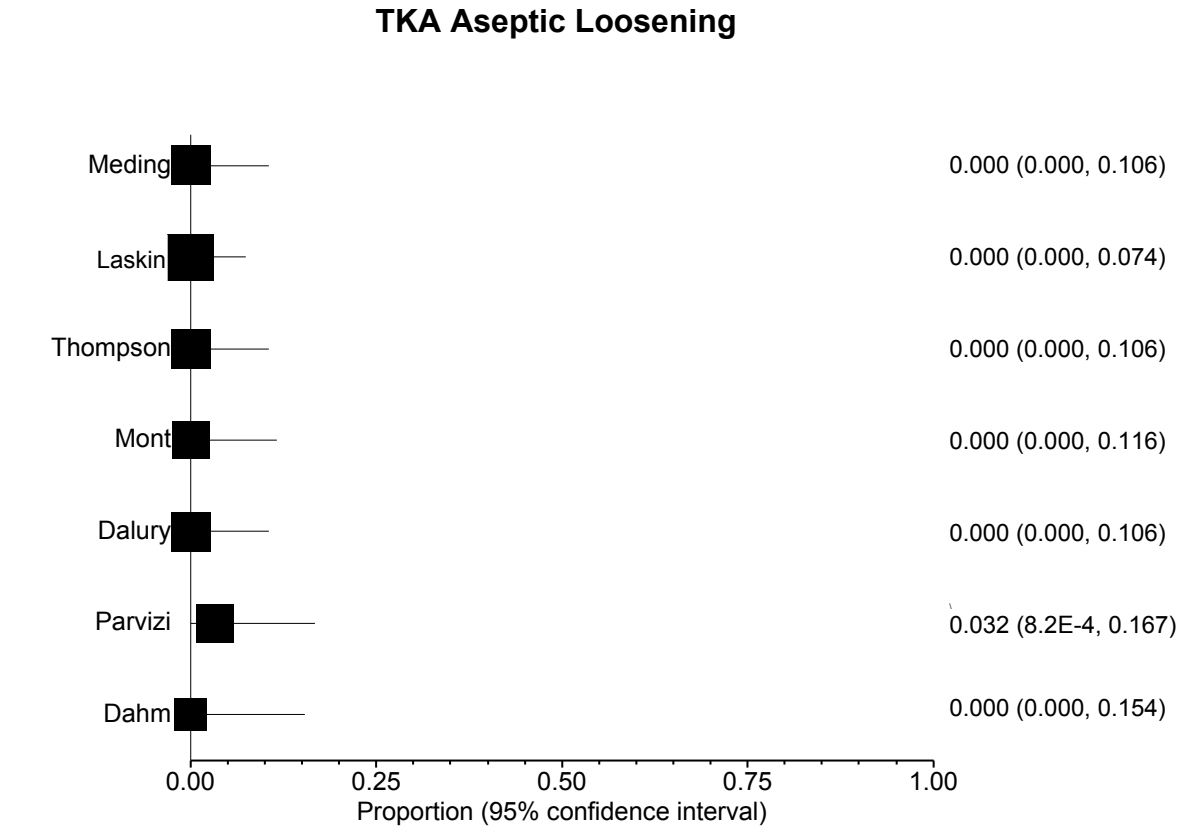


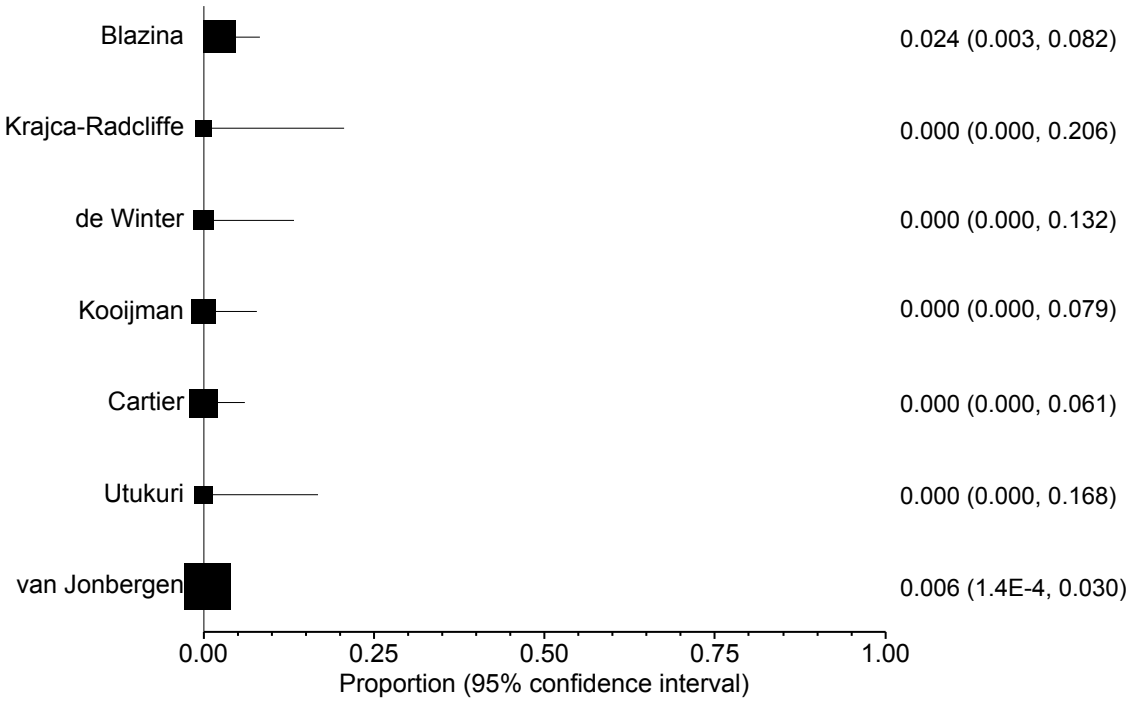
Figure 3-8 **Proportion of Aseptic Loosening**

Table 3-12 Proportion of Aseptic Loosening

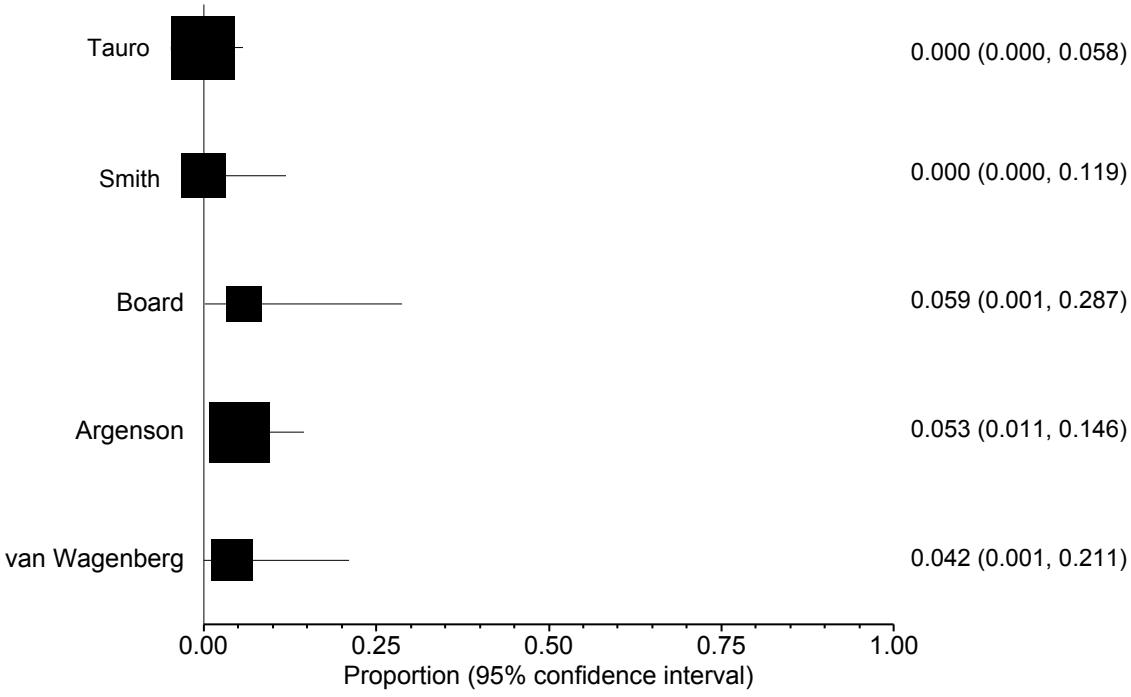
Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0	0	0.04	19.59
Krajca-Radcliffe 1996	0	0	0.21	3.87
de Winter 2001	0	0	0.13	6.15
Kooijman 2003	0.02	0	0.12	10.48
Cartier 2005	0	0	0.06	13.67
Utukuri 2008	0	0	0.17	4.78
van Jonbergen 2010	0.02	0.01	0.06	41.46
IAN				
Tauro 2001	0	0	0.06	32.47
Smith 2002	0	0	0.12	15.46
Board 2004	0.12	0.01	0.36	9.28
Argenson 2005	0.12	0.05	0.24	29.90
van Wagenberg 2009	0	0	0.14	12.89
IAA				
Merchant 2005	0	0	0.21	24.64
Charalambous 2011	0.24	0.13	0.37	75.36
OSN				
Nicol 2006	0	0	0.04	19.96
Ackroyd 2007	0	0	0.03	21.11
Hollinghurst 2007	0	0	0.26	2.50
Leadbetter 2009	0	0	0.05	15.36
Starks 2009	0	0	0.09	7.29
Odumenya 2010	0	0	0.07	9.79
Gao 2010	0	0	0.28	2.30
Sarda 2011	0	0	0.08	8.64
Mont 2012	0.15	0.04	0.25	8.45
Dahm 2010	0	0	0.15	4.61
OAA				
Hofmann 2009	0	0	0.09	35.65
Monk 2012	0	0	0.22	13.91
Mofidi 2012	0	0	0.10	30.43
Beitzel 2013	0	0	0.15	20.01
OAP				
Butler 2009	0	0	0.15	46.94
Sisto 2010	0	0	0.14	53.06
Mixed				
Arciero 1988	0	0	0.14	10.74
Arnbjornsson 1998	0	0	0.03	47.11
Mohammed 2008	0	0	0.04	42.15
TKA				
Meding 2007	0	0	0.11	14.35
Laskin 1999	0	0	0.07	20.68
Thompson 2001	0	0	0.11	14.35
Mont 2002	0	0	0.12	13.08
Dalury 2005	0	0	0.11	14.35
Parvizi 2001	0.03	0	0.17	13.50
Dahm 2010	0	0	0.15	9.70

* number of knees with aseptic loosening divided by the total number of knees assessed

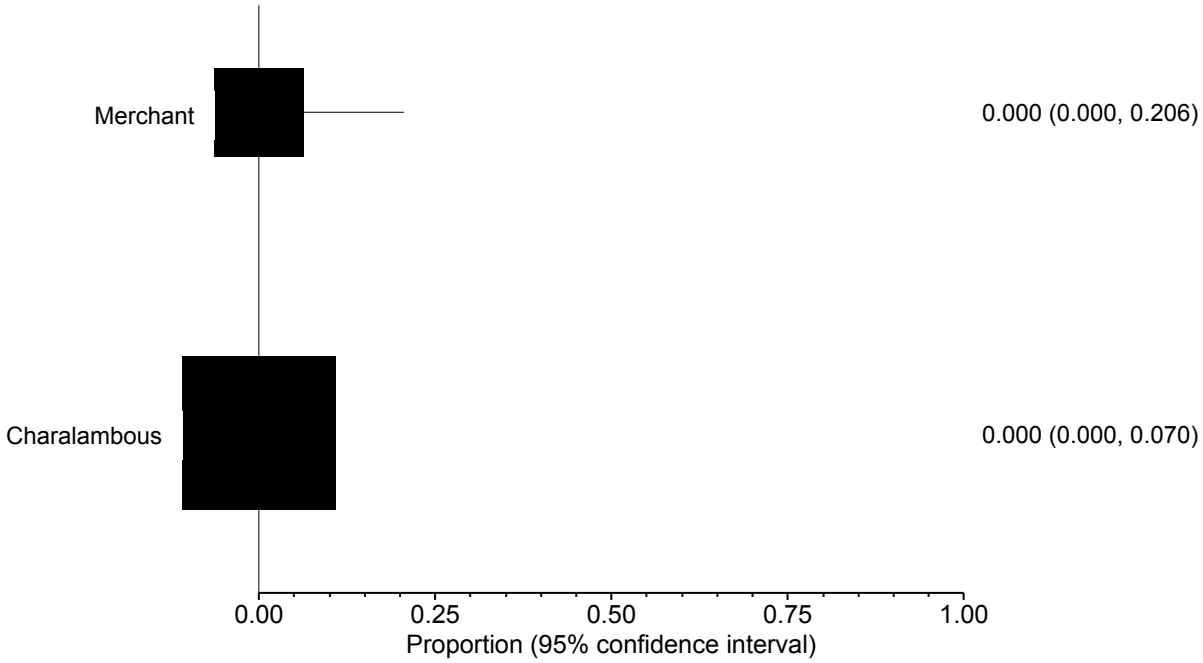
ISN Infection



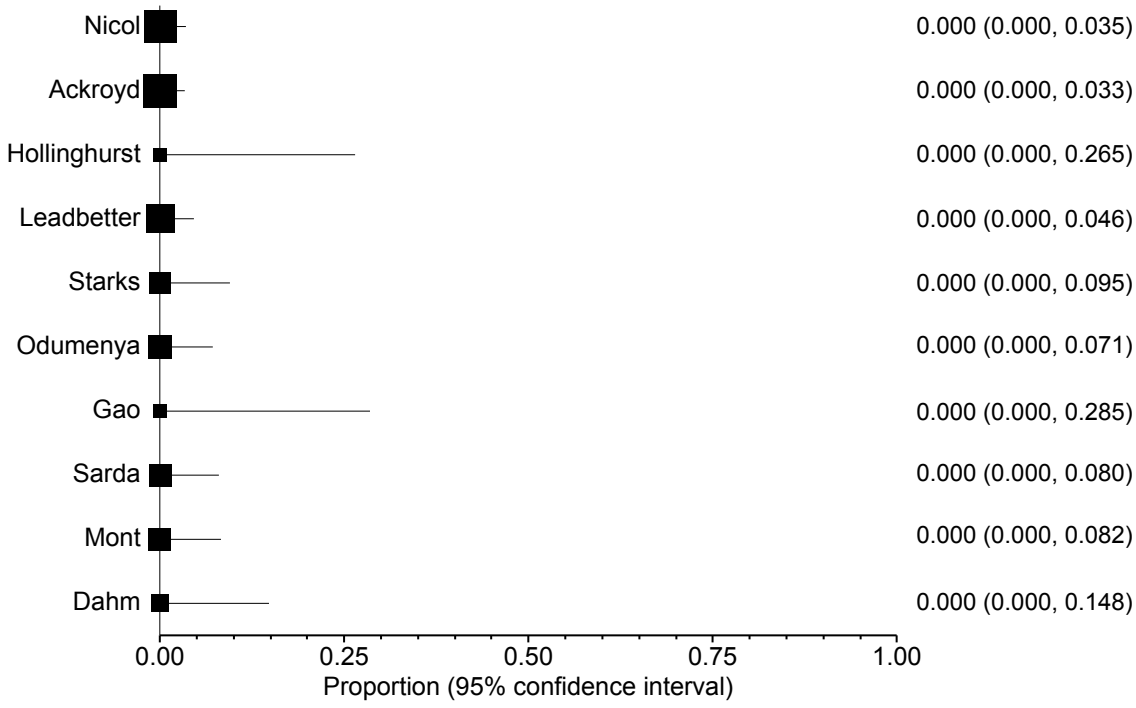
IAN Infection



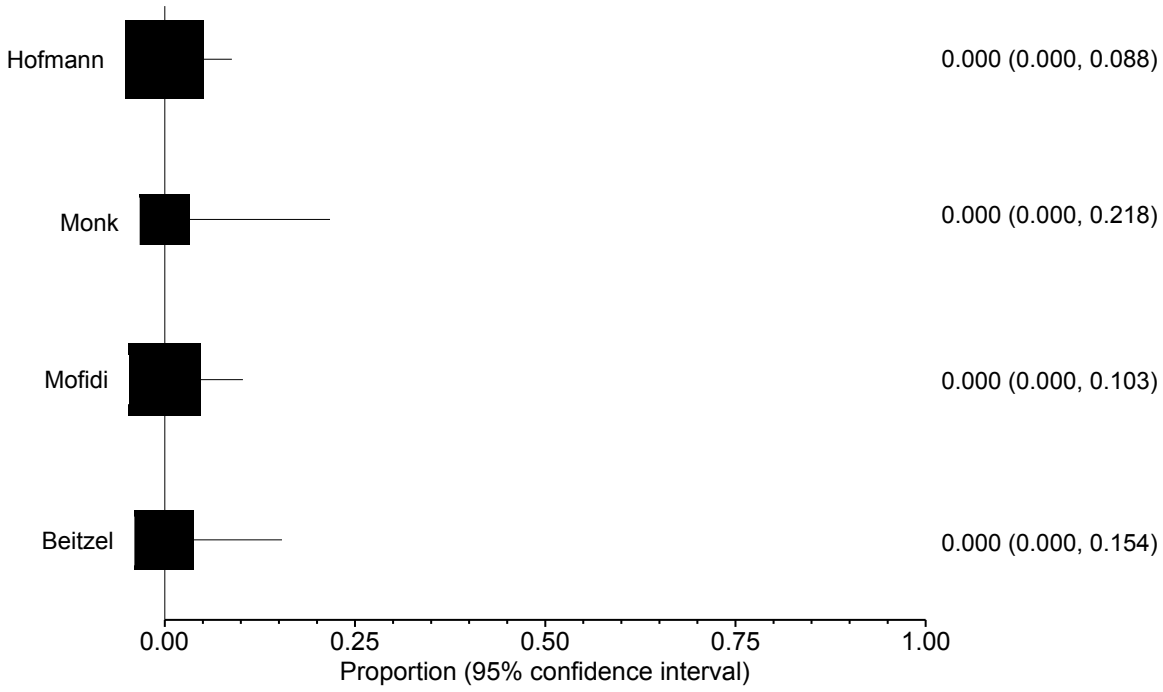
IAA Infection



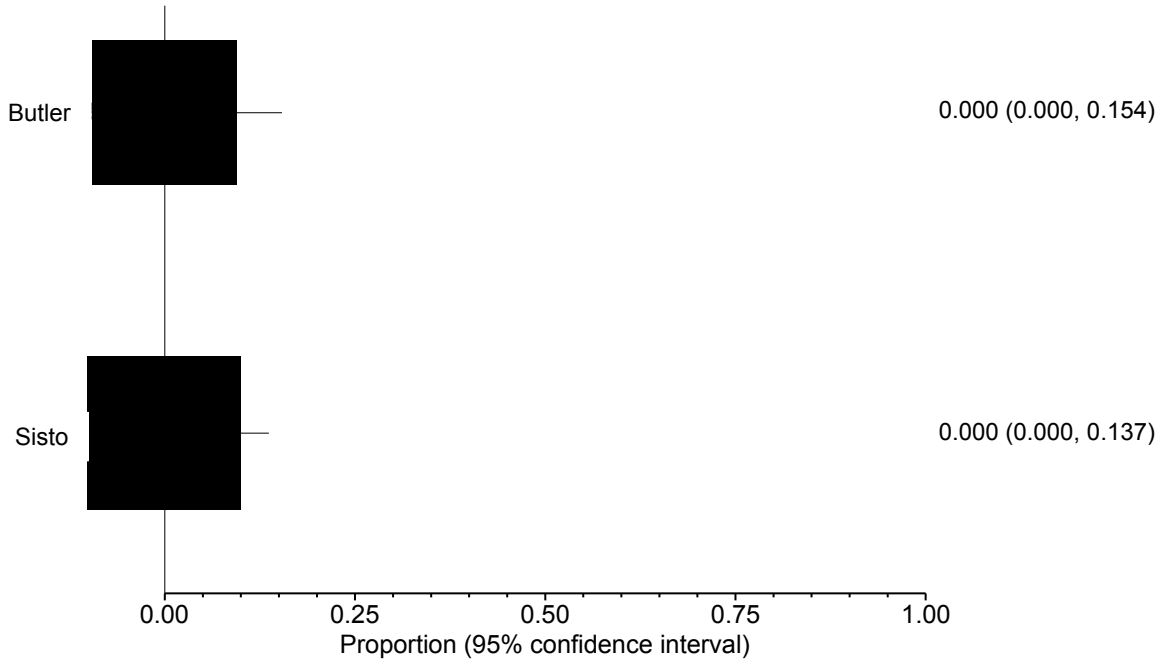
OSN Infection

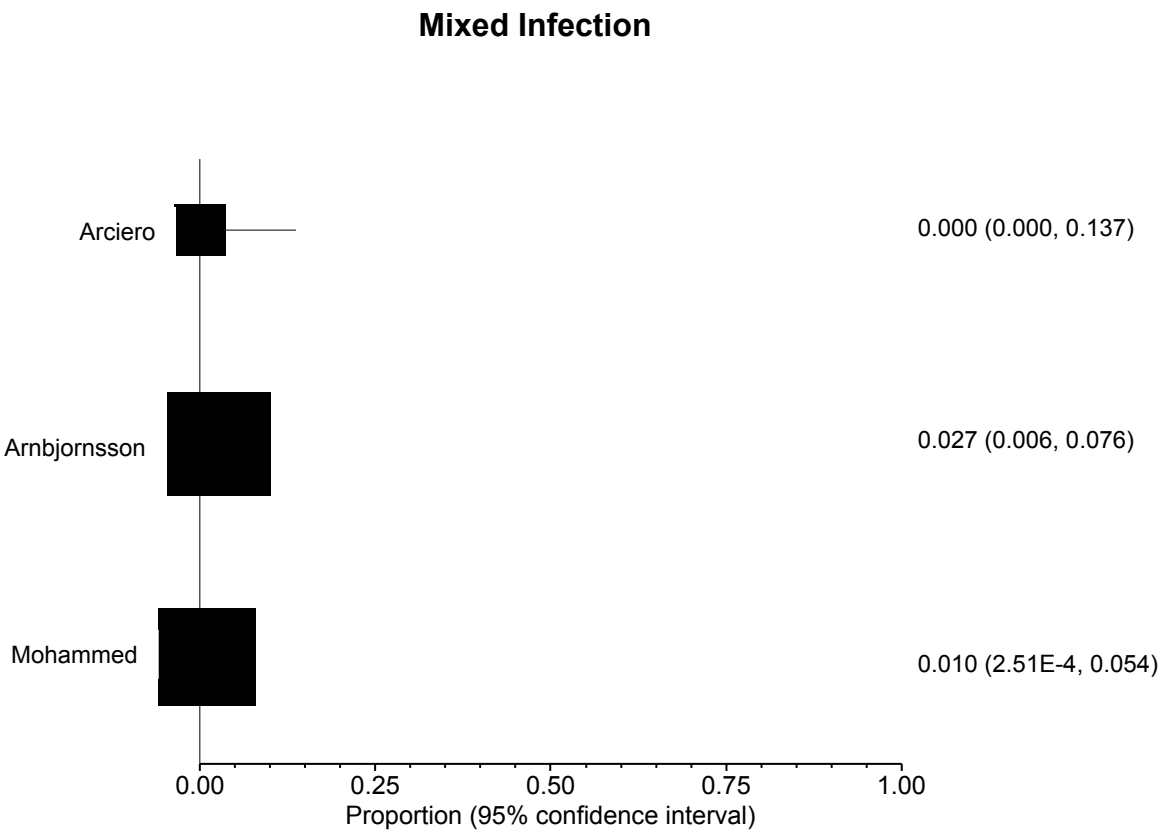


OAA Infection



OAP Infection





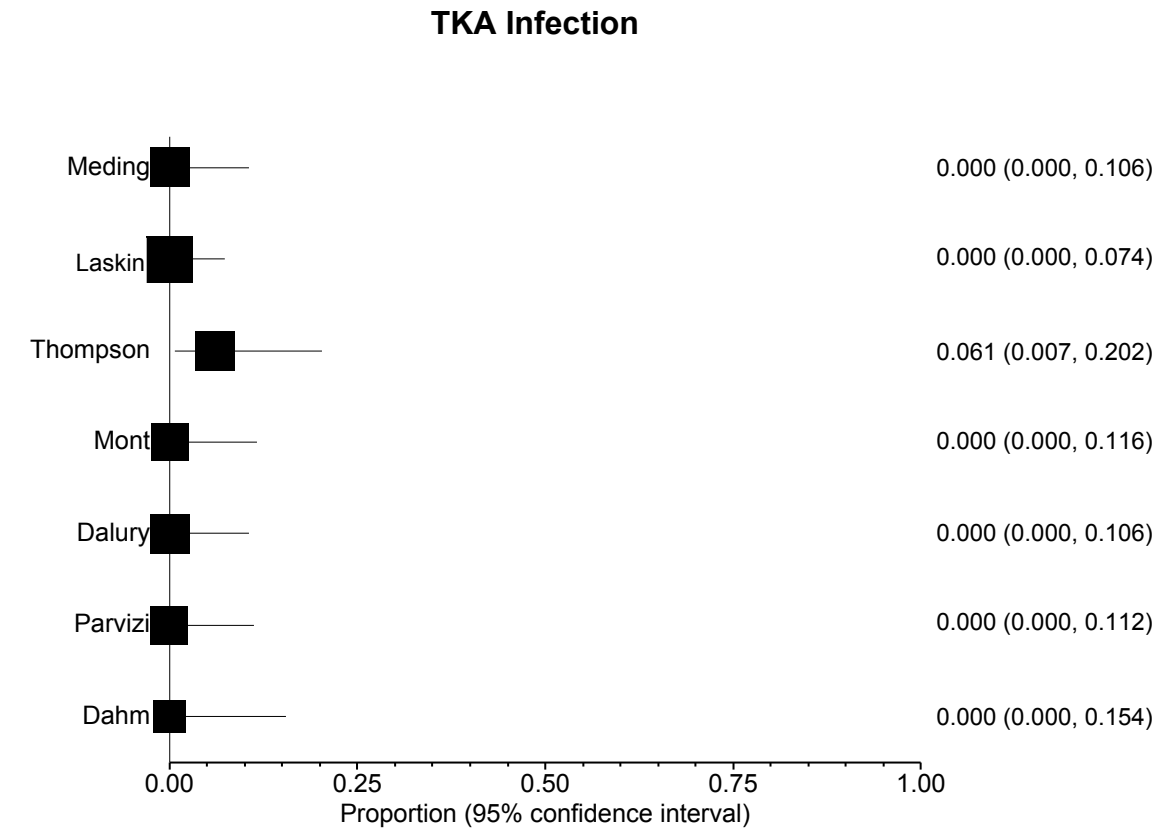


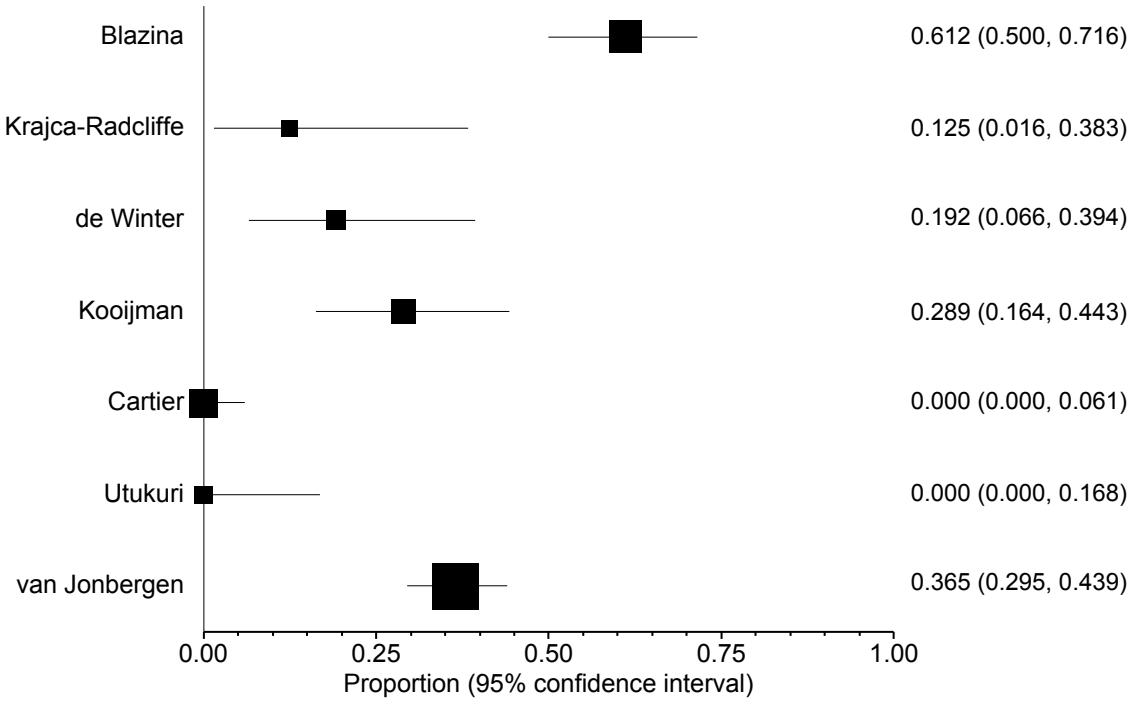
Figure 3-9 **Proportion of Infection**

Table 3-13 Proportion of Infection

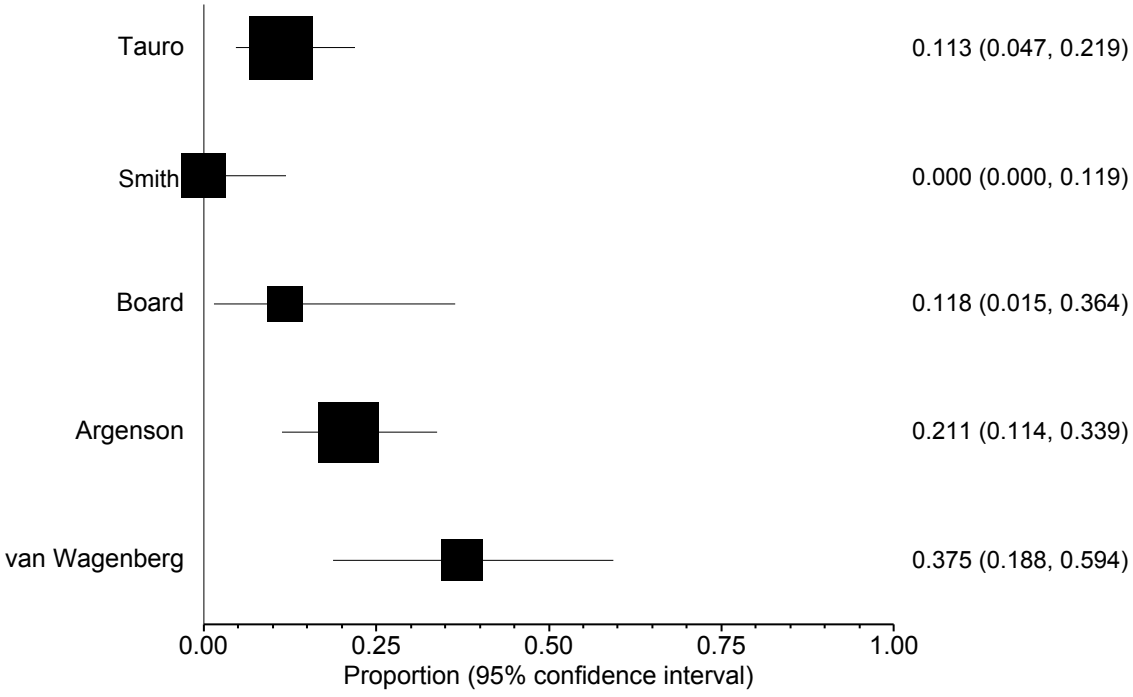
Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0.02	0	0.08	19.59
Krajca-Radcliffe 1996	0	0	0.21	3.87
de Winter 2001	0	0	0.13	6.15
Kooijman 2003	0	0	0.08	10.48
Cartier 2005	0	0	0.06	13.67
Utukuri 2008	0	0	0.17	4.78
van Jonbergen 2010	0.01	0	0.03	41.46
IAN				
Tauro 2001	0	0	0.06	32.47
Smith 2002	0	0	0.12	15.46
Board 2004	0.06	0	0.29	9.28
Argenson 2005	0.05	0.01	0.15	29.90
van Wagenberg 2009	0.04	0	0.21	12.89
IAA				
Merchant 2005	0	0	0.21	24.64
Charalambous 2011	0	0	0.07	75.36
OSN				
Nicol 2006	0	0	0.04	19.96
Ackroyd 2007	0	0	0.03	21.11
Hollinghurst 2007	0	0	0.26	2.50
Leadbetter 2009	0	0	0.05	15.36
Starks 2009	0	0	0.09	7.29
Odumenya 2010	0	0	0.07	9.79
Gao 2010	0	0	0.28	2.30
Sarda 2011	0	0	0.08	8.64
Mont 2012	0	0	0.08	8.45
Dahm 2010	0	0	0.15	4.61
OAA				
Hofmann 2009	0	0	0.09	35.65
Monk 2012	0	0	0.22	13.91
Mofidi 2012	0	0	0.10	30.43
Beitzel 2013	0	0	0.15	20
OAP				
Butler 2009	0	0	0.15	46.94
Sisto 2010	0	0	0.14	53.06
Mixed				
Arciero 1988	0	0	0.14	10.74
Arnbjornsson 1998	0.03	0	0.08	47.11
Mohammed 2008	0.01	0	0.05	42.15
TKA				
Meding 2007	0	0	0.11	14.35
Laskin 1999	0	0	0.07	20.68
Thompson 2001	0.06	0.01	0.20	14.35
Mont 2002	0	0	0.14	13.08
Dalury 2005	0	0	0.11	14.35
Parvizi 2001	0	0	0.11	13.50
Dahm 2010	0	0	0.15	9.70

*number of knees with infection divided by the total number of knees assessed

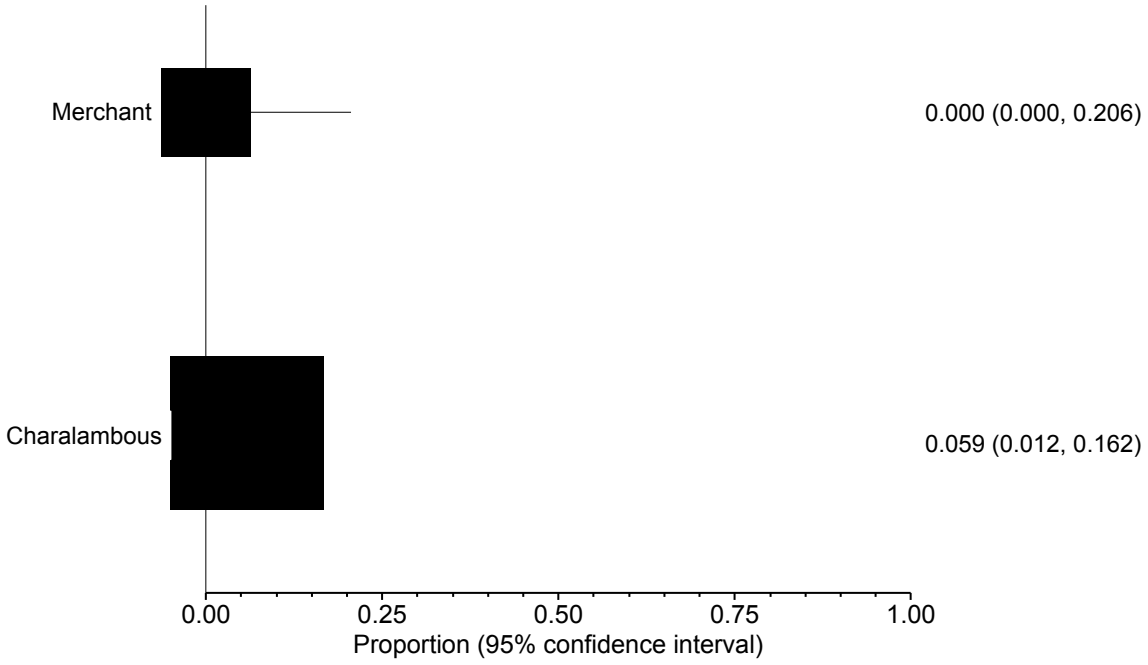
ISN Other Complications



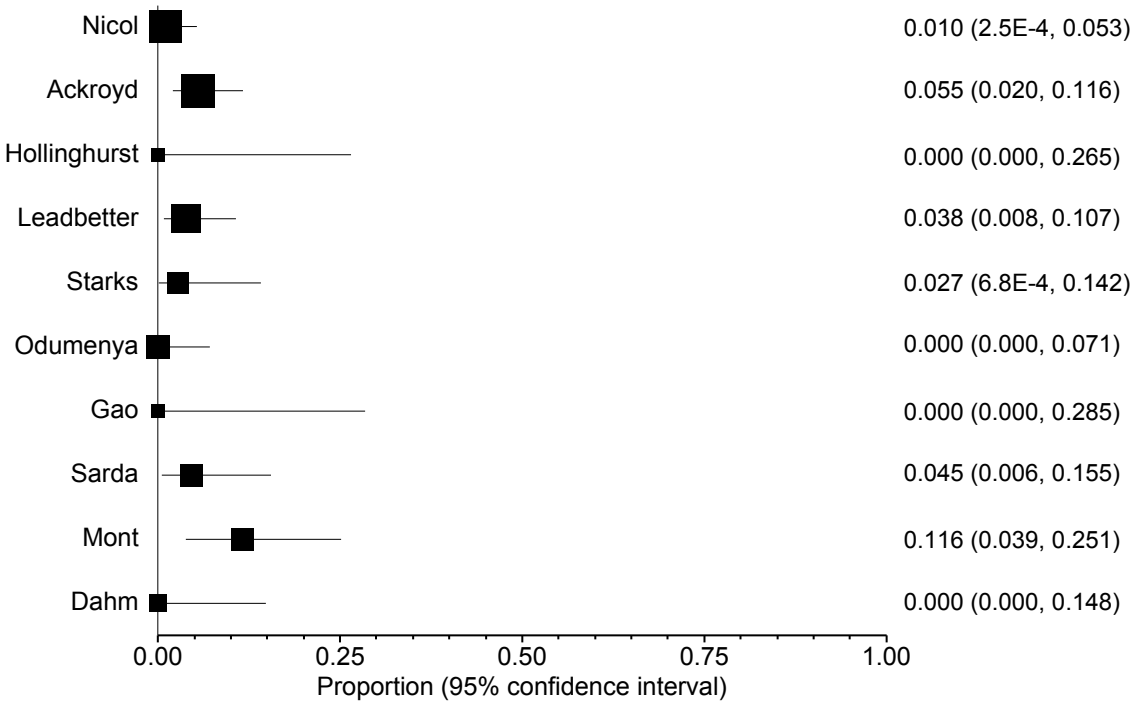
IAN Other Complications



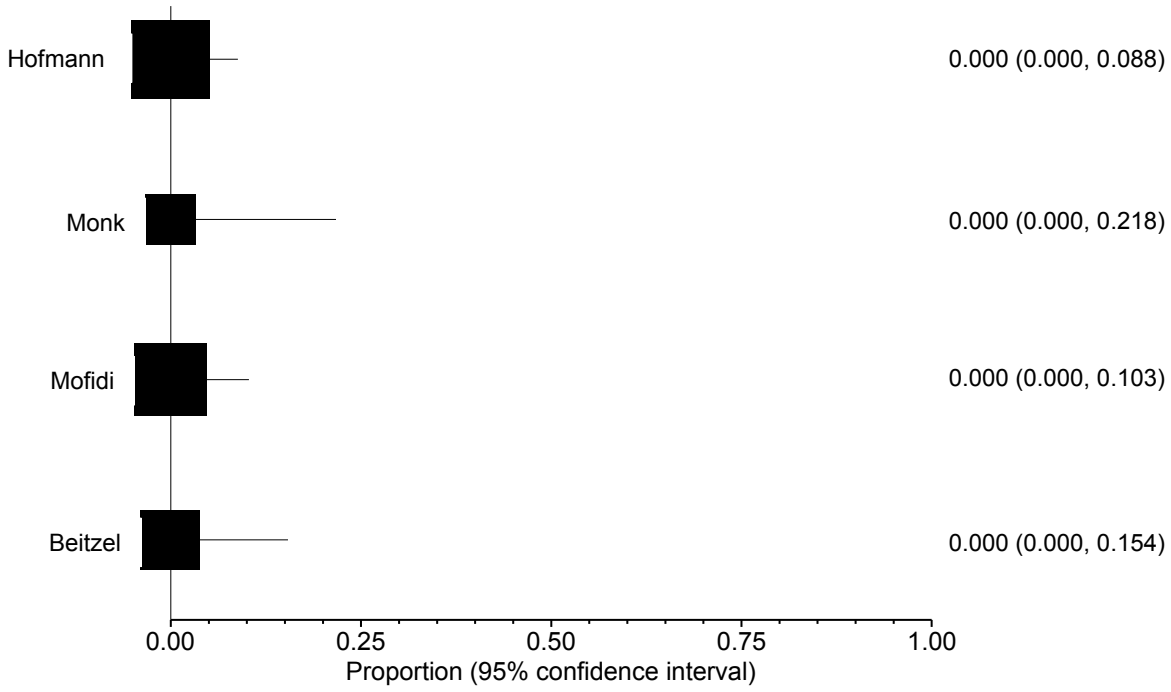
IAA Other Complications



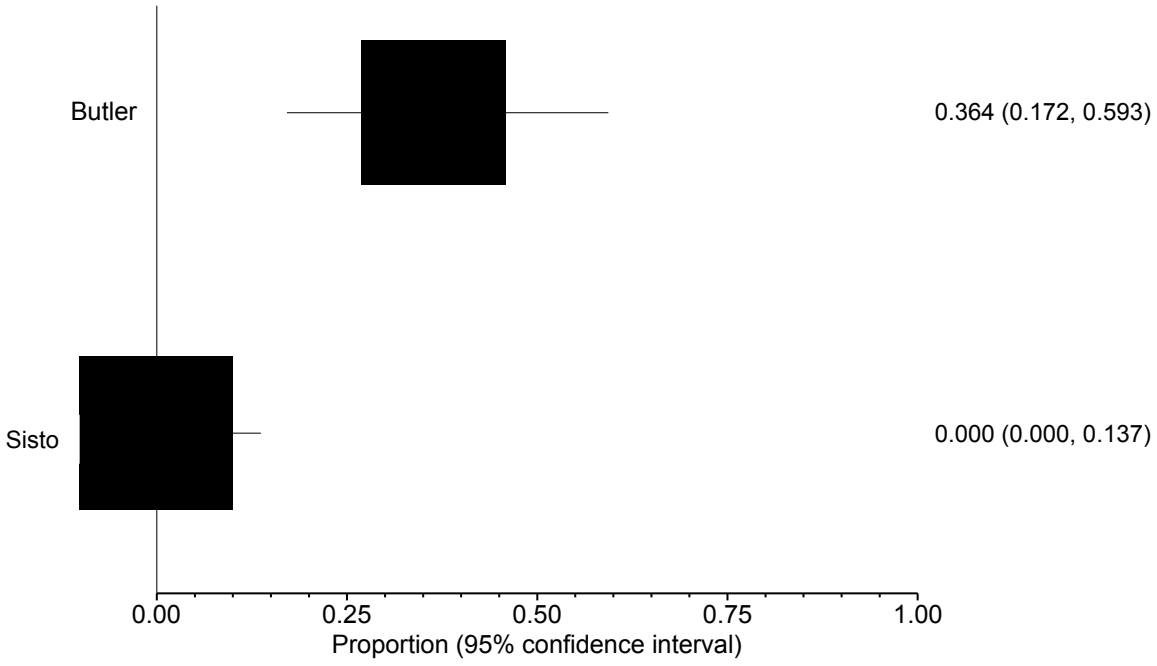
OSN Other Complications



OAA Other Complications



OAP Other Complications



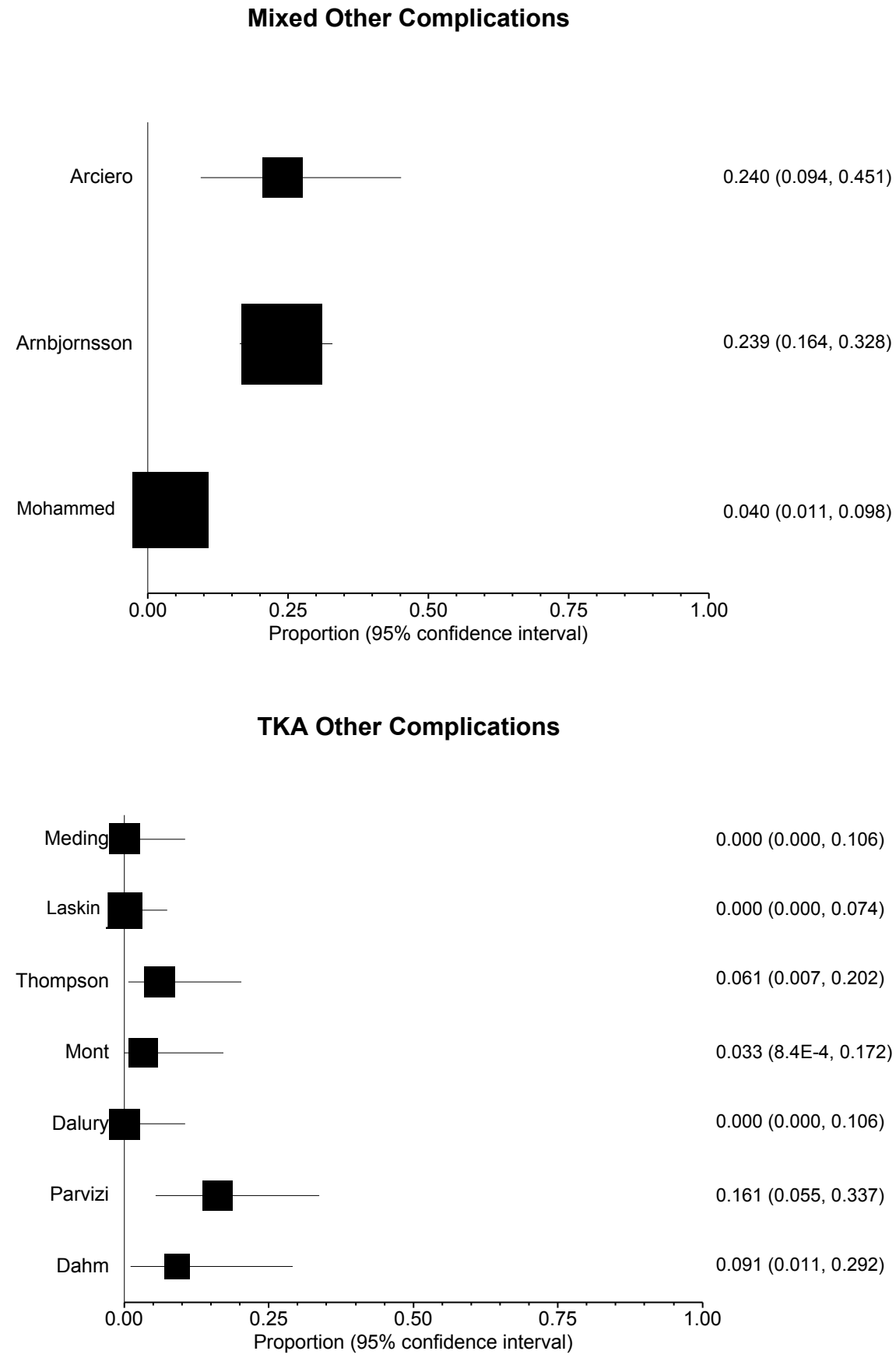


Figure 3-10 Proportion of Other Complications

Table 3-14 Proportion of Other Complications

Study	Proportion*	95% CI Lower Level	95% CI Upper Level	% weight (fixed)
ISN				
Blazina 1979	0.61	0.50	0.72	19.59
Krajca-Radcliffe 1996	0.13	0.02	0.38	3.87
de Winter 2001	0.19	0.07	0.39	6.15
Kooijman 2003	0.29	0.16	0.44	10.48
Cartier 2005	0	0	0.06	13.67
Utukuri 2008	0	0	0.17	4.78
van Jonbergen 2010	0.36	0.29	0.44	41.46
IAN				
Tauro 2001	0.11	0.05	0.22	32.47
Smith 2002	0	0	0.12	15.46
Board 2004	0.12	0.01	0.36	9.28
Argenson 2005	0.21	0.11	0.34	29.90
van Wagenberg 2009	0.38	0.19	0.59	12.89
IAA				
Merchant 2005	0	0	0.21	24.64
Charalambous 2011	0.06	0.01	0.16	75.36
OSN				
Nicol 2006	0.01	0	0.05	19.96
Ackroyd 2007	0.06	0.02	0.12	21.11
Hollinghurst 2007	0	0	0.26	2.50
Leadbetter 2009	0.04	0.01	0.11	15.36
Starks 2009	0.03	0	0.14	7.29
Odumenya 2010	0	0	0.07	9.79
Gao 2010	0	0	0.28	2.30
Sarda 2011	0.05	0.01	0.15	8.64
Mont 2012	0.12	0.04	0.25	8.45
Dahm 2010	0	0	0.15	4.61
OAA				
Hofmann 2009	0	0	0.09	35.65
Monk 2012	0	0	0.22	13.91
Mofidi 2012	0	0	0.10	30.43
Beitzel 2013	0	0	0.15	20.01
OAP				
Butler 2009	0.36	0.17	0.59	46.94
Sisto 2010	0	0	0.14	53.06
Mixed				
Arciero 1988	0.24	0.09	0.45	10.74
Arnbjornsson 1998	0.24	0.16	0.33	47.11
Mohammed 2008	0.04	0.01	0.10	42.15
TKA				
Meding 2007	0	0	0.11	14.35
Laskin 1999	0	0	0.07	20.68
Thompson 2001	0.06	0.01	0.20	14.35
Mont 2002	0.03	0	0.17	13.08
Dalury 2005	0	0	0.11	14.35
Parvizi 2001	0.16	0.05	0.34	13.50
Dahm 2010	0.09	0.01	0.29	9.70

*number of knees with other complications divided by the total number of knees assessed

3.6.6 Functional Outcomes

The reporting of functional outcomes varied considerably from study to study therefore limiting the comparisons and inferences that could be drawn. For example, the specific score values were often not presented, instead a percentage of the sample population that reached a certain score range was stated. Others devised a secondary categorical scale to represent the original nominal data as 'excellent, good, fair, poor/failure'. In additional, the majority of the selected articles were retrospective and therefore not all had pre-operative data available for assessment of improvement. Furthermore, the follow-up times varied within and between the groups considerably which also added to the difficulty in drawing conclusions. A summary of the functional outcome data is in Appendix VI in Table 6-43. All references made in the summary of findings below correspond with this table.

Inlay symmetrical non-anatomical

Prostheses: Richards I and II (two studies); Richards II (five studies)

Five out of seven studies (Cartier *et al.*, 2005; de Winter *et al.*, 2001; Kooijman *et al.*, 2003; Krajca-Radcliffe & Coker, 1996; Utukuri *et al.*, 2008) reported functional data of which one had pre-operative scores (Utukuri *et al.*, 2008). The most common score used was the AKSS although a summary of findings was limited due to variations in reporting style; other scores reported were the Hungerford and Kenna Scale, HSS,

SF-36 and KOOS. Overall, the studies suggested excellent outcomes, rated as approximately 85 to 100 (for all scores with maximum 100 best outcome) occurred in the majority of the sample populations. Satisfaction was also reported by three studies, all of which found good to excellent outcome majority.

Inlay asymmetrical non-anatomical

Prostheses: Lubinus (three studies); Autocentric (one study); Autocentric II (one study)

All five studies reported functional results of which three had pre-operative data in selected scores (Argenson *et al.*, 2005; Board *et al.*, 2004; Tauro *et al.*, 2001). The studies with pre- and postoperative scores showed functional improvement although the range of the data was wide. For example, the Bristol Knee Score improved from mean 55 (29 - 86) to mean 72 (42 - 100) at mean 7.5 years follow-up (Tauro *et al.*, 2001) and AKSS function/clinical results improved from mean 41 (10 - 80)/53 (43 - 70) to mean 81 (40 - 100)/79 (60 – 100) at 16.2 years (Argenson *et al.*, 2005). The KOOS score was presented as separate scores for the individual subsections, ranging from 22 - 60 each out of 100 at 4.8 years follow-up with sport and recreation function scoring the lowest at 22±13 (van Wagenberg *et al.*, 2009). The low mean functional outcome scores, such as the Lysholm and the KOOS, were also reflected in the lower

survival proportions and higher number of complications associated with these studies.

Inlay asymmetrical anatomical

Prosthesis: LCS (two studies)

Four validated scores were used to assess function post-operatively in both studies. Merchant (2005) used The Activity of Daily Living Scale to measure function pre- and post-operatively in only half of the patients (eight knees), reporting post-operative mean 84% (the equivalent of excellent; scores ranged between 74% and 96%) compared to pre-operative mean 42% (the equivalent of poor; scores ranged between 23% and 73%). The applicability of this data is limited by the small sample, therefore little inference can be made based on these results. The other study in this group (Charalambous *et al.*, 2011), reported post-operative scores for AKSS Function/Clinical: 80 (63 - 100)/ 87 (63 - 88), OKS (35 (26 - 44) and Melbourne Patellar Score 25 (16 - 30), all of which were satisfactory. However, without pre-operative data there is no indication whether the intervention led to an improvement in function. Satisfaction was also measured and the majority of patients deemed their level as 'better'.

Onlay symmetrical non-anatomical

Prosthesis: Avon (nine studies)

Five out of the nine studies had pre- and post-operative data (Ackroyd *et al.*, 2007; Gao *et al.*, 2010; Leadbetter *et al.*, 2009; Mont *et al.*, 2012; Sarda *et al.*, 2011). One study (Nicol *et al.*, 2006) did not report any functional scores and the remaining three (Hollinghurst *et al.*, 2007; Odumenya *et al.*, 2010; Starks *et al.*, 2009) presented post-operative data only. Four out of the five studies with pre- and post-operative data reported the AKSS outcome and demonstrated an improvement post-operatively. Pre-operative AKSS function mean range of 42 - 57 and AKSS clinical mean range of 49 - 64 compared to the post-operative AKSS function mean range of 67 - 95 and AKSS clinical mean range of 80 - 96. There was no association between higher scores and shorter follow-up time; generally the post-operative scores were similar for all four studies. Satisfaction data also revealed the majority of patients were satisfied with the procedure.

Onlay asymmetrical anatomical

Prostheses: Natural Knee II (one study), Femoro Patella Vialla (three studies), Journey (one study)

Two out of five studies reported pre- and post-operative OKS and AKSS scores both of which demonstrated improvements in function (Mofidi *et*

al., 2012; Monk *et al.*, 2012). Hofmann *et al*. (2009) reported an improvement in Tegner score from level three pre-operatively to level five, implying patients were able to carry out heavy duty tasks and participate in competitive and recreational sports post-operatively. This finding supported the KOOS subsection satisfactory scores of between 70 and 94 determined post-operatively in the same study. This study also assessed patient satisfaction and reported all the patients were satisfied. Out of the remaining two articles, one study (Williams *et al.*, 2013) did not analyse function using scores and the other (Beitzel *et al.*, 2013) reported improvements in WOMAC, Lysholm and VAS (pain) but did not offer specific values allowing for objective assessment of the results by the reader.

Onlay asymmetrical patient-specific

Prostheses: Custom Performa Knee (one study), Kinematch (one study)

One out of two of the studies in this group reported the WOMAC score, a validated functional outcome, both pre- and post-operatively and showed an improvement from mean 63 to 28 (Butler & Shannon, 2009). The major limitation with this data is that both the pre- and post-operative data were collected at the same post-operative time point and therefore is susceptible to recall bias. The other study presented only satisfaction outcome and found all 25 patients were very satisfied. Ideally, a validated

patient-reported outcome would have offered more robust evidence of clinical outcome.

Mixed group

Prostheses: Richards I and II, CSF-Wright, Lubinus, Avon, FPV and miscellaneous other (not specified)

Mohammed *et al*. (2008) did not report any functional scores. One study (Arnbjörnsson & Ryd, 1998) presented unsatisfactory Lysholm scores, suggesting at least one patient was worse after surgery (pre- and post-operative as mean 45 (20 - 64) and 62 (6 - 100), respectively). In addition, 25% of the patients (28 out of 113) in this study were dissatisfied with the outcome following surgery. The remaining study (Arciero & Toomey, 1988) in this group presented post-operative Modified Hungerford and Kenna scale scores, with a majority rating good or excellent (nine knees: 80 - 89; nine knees: ≥ 90), however, seven knees rated as poor, scoring < 70. No indication was given to suggest these less satisfactory results were associated with one particular prosthesis.

Total knee arthroplasty

Prostheses: Anatomical Graduated Component (AGC), Legacy, Genesis, Low Contact Stress (LCS), Porous Coated Anatomic, Duracon, Insall-Burstein II, Press Fit Condylar (PFC), Total Condylar

Five out of six of these studies (Dalury, 2005; Laskin & van Steijn, 1999; Meding *et al.*, 2007; Mont *et al.*, 2002; Parvizi *et al.*, 2001) reported pre- and post-operative AKSS scores, the remaining study (Thompson *et al.*, 2001) did not report any validated functional outcome data. Each study demonstrated an improvement in function and clinical outcomes: function pre-op mean range 36 to 71 and post-op mean range 83 to 96, clinical pre-op mean range 25 to 54 and post-op mean range 47 to 93. The high survival proportions and low number of complications are reflected in these relatively high post-operative functional scores.

Comparison

Prostheses: Avon, Zimmer TKA and SIGMA

One comparison study (Dahm *et al.*, 2010) reported pre- and post-operative AKSS, Tegner and UCLA scores following Avon PFA in one group and Zimmer or SIGMA TKA in another group. All three scores improved for both groups significantly, however there were no statistically significant differences between the groups at short follow-up of means 2.3 years (PFA) and 2.4 years (TKA).

3.7 Discussion and Critical Appraisal

The principal aim of this systematic review was to determine the survival proportions and complications following PFA and TKA using the new design categorisation system introduced in this study.

Two survival proportions were assessed, Survival Proportion A, defined as the surviving number of implants, that is, the total number of knees minus the number of knees that suffered the endpoint event - revision to TKA due to disease progression, divided by the total number of knees assessed in the sample population and Survival Proportion B, as the surviving number of implants, that is, the total number of knees minus the number of knees that suffered the endpoint events - revision any reason to TKA, revision to another PFA, removal of PFA or arthrodesis, divided by the total number of knees assessed in the sample population. The design categories were: inlay symmetrical non-anatomical (ISN), inlay asymmetrical non-anatomical (IAN), inlay asymmetrical anatomical (IAA), onlay symmetrical non-anatomical (OSN), onlay asymmetrical anatomical (OAA), onlay asymmetrical patient-specific (OAP), mixed and TKA.

The forty studies reviewed in this systematic review were placed in the respective design categories and analysed within and between the groups. Due to the heterogeneity of the studies within each group a meta-analysis and inferential statistics were not performed, instead the analysis carried out was descriptive. The studies were all observational, the majority (36) being retrospective uncontrolled case series'. This type of

study design is subject to a number of biases and limitations. This discussion focuses on evidence in relation to the prosthetic designs, the quality of the evidence presented in each group and the limitations of drawing conclusions from these studies.

Inlay symmetrical non-anatomical

Prostheses: Richards I and II (two studies); Richards II (five studies)

The overall quality of the literature presented in this group was 'low' in accordance with the GRADE assessment system due to all the studies being uncontrolled retrospective case series'. The majority of the studies did define the study objectives, population and eligibility criteria. However, the data collection and analyses were often carried out by or involved the operating surgeon, which increased the risk of selective reporting bias. In addition, only the more recent studies clearly defined the intervention (surgeon, surgical approach, post-operative rehabilitation). The outcomes used in the studies were appropriate and the conclusions drawn were supported by the results presented. The length of follow-up varied greatly between the studies although three out of seven were long-term studies (de Winter *et al.*, 2001; Kooijman *et al.*, 2003; van Jonbergen *et al.*, 2010b). The loss to follow-up was very high in this group. Approximately, 26% (155 out of 587) of knees within this group were excluded from data analysis. Cartier *et al*. (2005) reported a 35% loss to follow-up (33

patients lost to follow-up and five deceased), such large numbers omitted from the analysis ultimately compromises the validity of the findings presented. It is therefore possible that the survival and complication outcomes were poorer than those presented. The results, albeit undermined by the missing data, showed disease progression was the commonest mode of failure although 'other' and malpositioning/misalignment were the most frequently recorded complications. These may have been related to the Richards I prosthetic design.

The Richards prostheses, also known as, Blazina and Bechtol I, II and III (Smith & Nephew Richards Inc., Memphis, Tennessee) have a deep trochlear groove, which provides great stability. However, this high level of stability is not always advantageous, because it can sustain higher shear forces, if the soft tissues are unbalanced, possibly leading to loosening and rapid wear. Other drawbacks include increased bone loss to inset the prosthesis and prominent edges, which may cause soft tissue impingement. Cartier *et al*. (2005) reported patellar snapping and lateral patellar pain due this prominence. The deep constraining geometry of the trochlea requires accurate alignment of both the trochlear and patellar components, failure to do so may have resulted in the high number of reported cases of maltracking and catching of the patellar component on the already prominent edge of the trochlear prosthesis. De Winter *et al*. (2001) followed 26 patients for a mean of 11.1 years and recorded that 11 had undergone further surgery (three patellectomies, three arthroscopic

washouts, two patellar realignments, two TKAs and two manipulations under anaesthesia). Kooijman *et al*. (2003) reported, at a mean of 17.0 years follow-up, 27 reoperations in 45 PFAs, of which seven involved corrective surgery for either patellofemoral symptoms such as catching or prosthesis malpositioning. The most recent series, at 13.3 years median follow-up, identified 95 further operations performed in 67 out of 157 patients of which at least 20 were for malpositioning, loosening or wear (van Jonbergen *et al.*, 2010b).

This category had the highest number of pre index arthroplasty operations. It is therefore difficult to determine which complications are partly related to or a result of previous surgeries. Blazina *et al*. (1979) suggested patellar tendon shortening prior to arthroplasty surgery may have resulted in raised patellofemoral compression pressure causing persistent pain on knee flexion beyond 90°. Patella baja has been suggested as a contraindication to PFA surgery (Cartier *et al*., 2005). However, it is difficult to be certain this was the main problem as over 200 procedures were carried out post index procedure compared to 31 concomitantly which would suggest that problems also arose secondary to prosthesis implantation (see Table 6-41).

The importance of patient selection is highlighted in this category. De Winter *et al*. (2001) found none of the 19 PFAs that had no medial or lateral tibiofemoral arthritis pre-operatively were revised. Only one of the 19 knees developed tibiofemoral arthritis grade 2 at 18.8 years follow-up unlike those with pre-operative medial or lateral tibiofemoral arthritis. Out

of those seven PFAs with evidence of tibiofemoral disease two were revised to TKAs. Whilst this is not conclusive evidence, it does support the argument for further research into the indications for PFA surgery. In addition, inadequately treated patellar instability, abnormal Q angles and increased tibial tuberosity trochlear groove (TTTG) distance would have also impacted the outcomes.

Inlay asymmetrical non-anatomical

Prostheses: Lubinus (three studies); Autocentric (one study); Autocentric II (one study)

The articles in this category were also graded as 'low' in accordance with the GRADE assessment system. All five retrospective studies clearly stated study objectives and defined the study population (inclusion/exclusion criteria). The authors were explicit about the interventions and the outcome tools used to assess the treatment. The length of follow-up was clearly stated in each study. Unlike the previous group (inlay symmetrical non-anatomical) there were fewer patients lost to follow-up (including deceased) thus comparatively the applicability of the data was not compromised by this potential weakness. The majority of the studies based the conclusions on the study findings presented except Argenson *et al*. (2005). The authors of this study declared first line treatment for elderly patients should be TKA even though this was not assessed in this study.

Higher numbers of complications occurred with the Lubinus PFA (Waldemar Link, Hamburg, Germany) (Tauro *et al.*, 2001) as reflected by poorer survival proportions than the Richards prostheses (see Table 3-4, Table 3-5 and Table 3-6). The dimensions of the Lubinus trochlear prosthesis and matching patellar component both varied depending on the size. The 'extra-large' size had a very shallow groove and was described as a 'skid prosthesis' (Ackroyd, 1996). The patellar component skidded about the surface of the trochlear component and was susceptible to maltracking. The other two sizes had a narrow medial-lateral width, and a deep constraining groove in the axial plane. Additionally, these sizes had a relatively short anterior flange allowing the patellar component to contact the anterior cortex of the femur in full knee extension. The transition from the anterior femur to the trochlear component was not always smooth because in the sagittal plane the implant was less curved than the distal femur. Either the implant was fixed flush in the notch, which elevated the proximal end causing symptoms of patellar catching on engagement at the start of flexion, or it was placed with the proximal end flush on the femur, which risked impingement on the tibia or anterior cruciate ligament in extension. Tauro *et al*. (2001) found out of 76 Lubinus arthroplasties, 24 had patellar misalignment and a further 21 required revision surgery of which 15 were for patellar maltracking. Therefore 51% of knees had patellofemoral dysfunction, matching the high rate of unsatisfactory clinical outcome (55%) (Tauro *et al.*, 2001). Although the designs of these prostheses

contributed to the complaints of patellar instability, it is plausible that this prevalence of patellar maltracking also resulted from lack of instrumentation to align the PFA components, and insufficient appreciation of the methods needed to balance the soft tissues. Tauro *et al*. (2001) reversed the trochlear component in an attempt to resolve issues of instability, however eight of the 21 patients that required revision surgery had reversed trochlear components. Snapping, clunking or subluxation and anterior knee pain were the most common symptoms (Smith *et al.*, 2002; Tauro *et al.*, 2001). Smith *et al*. (2002) highlighted the importance of patient selection, reporting the worse results were identified in the patients with evidence of medial tibiofemoral compartment arthritis pre-operatively. Out of these eight patients six underwent revision surgery or had unsatisfactory results.

The Autocentric (Depuy, Warsaw, Indiana) prosthesis was developed in 1980 by Grammont and Millon. The trochlear component was asymmetric, curved in both the sagittal and frontal planes, and the patellar component was designed as a self-centering device. The poor clinical outcomes and failure proportions, as high as 51% (Argenson *et al.*, 2005), mainly due to loosening, stiffness, instability and disease progression, led to the withdrawal of this prosthesis (Argenson *et al.*, 2005; Gadeyne *et al.*, 2008; van Wagenberg *et al.*, 2009). Argenson *et al*. (2005) found disease progression most commonly occurred in patients with primary arthritis, compared with three out of 21 patients with patellar instability and three out of 18 patients with post-traumatic arthritis.

Inlay asymmetrical anatomical

Prosthesis: LCS (two studies)

The ‘very low’ GRADE classification was assigned to this group because of the degree of study limitations (biases) and imprecision (low patient numbers) identified. In general, both studies stated clear objectives, explicit inclusion and exclusion criteria and specified the time when recruitment occurred or dates of the index procedures. Clinically relevant outcomes were used in both studies and neither reported any loss to follow-up. However, consecutive patient inclusion was not explicitly stated and there was no comparator group in either study. The main criticism of this group lies with the study performed by the designing surgeon. The design surgeon, who also carried out 50% of the procedures, collected the pre- and post-operative data and sourced the additional eight cases from five other surgeons. No indication is given as to how these patients were selected and therefore the data is susceptible to selection and reporting bias. The ‘large’ statistically significant difference found between the pre- and post-operative ADL score was misinterpreted as an indicator of the benefits for stringent patient selection. The *p* value size is not an indicator of strength of association, it is rather a measure of the chance of getting this result when no real difference in scores actually existed. In order to prove the effects of this patient selection, with such a small cohort (16 patients), a modified study design with a statistical power

calculation showing that this was an adequate number would need to be performed to validate the author's interpretation.

The Low Contact Stress (LCS) Patello-Femoral Joint (Depuy Orthopedics, Warsaw, Indiana) was based on the LCS total knee arthroplasty, and adopted the inlaid trochlear design of the Richards but produced less favourable results mainly due to patellar component failure (Amanatullah & Jamali, 2012; Arumilli *et al.*, 2010; Charalambous *et al.*, 2011) despite early reports of success (Merchant, 2004; Merchant, 2005).

The LCS modular two-part patellar component consisted of a metal plate for bone fixation and a mobile polyethylene bearing (Garcia *et al.*, 2008). The concept was that the patella would be self-aligning within the trochlear groove to enhance tracking. However, the independent study revealed at two years 31% (17 out of 51) had already undergone revision of which only two were related to tibiofemoral disease progression (Charalambous *et al.*, 2011) leading to survival proportion B of 67% or only 46% (95%CI 30% to 63%) survivorship at three years with severe pain or revision as the endpoint. The high failure proportion was most likely a result of dissociation of the polyethylene from the metal base and loss of mobility, and significant metallosis due to metal-on-metal articulation of the trochlea with the metal base of the patellar component. This prosthesis has now been discontinued due to these poor results (Charalambous *et al.*, 2011).

Onlay symmetrical non-anatomical

Prosthesis: Avon (nine studies)

The GRADE classification for this group was ‘low’. The main criticism of these studies was the lack of comparator group and retrospective evaluation. Only two out of the nine studies were prospective. The issue with the remaining seven retrospective studies were the high risk of biases. The quality of these studies was dependent on the accuracy and accessibility of the medical notes and patients (reporting bias). In addition, the investigator selected (selection bias) the cases even though the patients were stated to be consecutive. Other weaknesses include the majority of follow-up was short-term; only four studies presented mid-term results (Ackroyd *et al.*, 2007; Mont *et al.*, 2012; Nicol *et al.*, 2006; Odumenya *et al.*, 2010). The authors of two of the studies involved the design surgeon and therefore the results may not be as reproducible in an independent centre. The small loss to follow-up (18 in the entire group) maintained the generalisability of each study’s findings and minimised the potential biases that occur due to incomplete follow-up. For each study, the basic study objectives, sample population defined and location of data collection were clearly stated. The outcomes were stated explicitly and relevant to the predetermined objectives. The statistical analyses described were appropriate for the data collected and the interpretation of these results was consistent with the findings.

The Avon Patello-Femoral Joint Replacement System (Stryker® Howmedica Osteonics, Allendale, New Jersey) was based on the Kinemax total knee replacement (Hsu & Walker, 1989; Walker, 1991) and was designed with the aim of addressing the limitations of the earlier designs (see Appendix VI: Differences in Geometry) and thus produced better clinical results with fewer patellofemoral symptoms (Ackroyd, 2005; Ackroyd *et al.*, 2007; Hendrix *et al.*, 2008; Odumenya *et al.*, 2010; Starks *et al.*, 2009). The survival proportions and survivorship data, summarised in Table 3-4, suggested higher survival was associated with this design group. Ackroyd *et al.* (2007) reported less than 1% incidence of patellar maltracking. Complications such as malpositioning/misalignment occurred far less frequently than with the ISN and IAN designs as illustrated in the six complication forest plots Figure 3-5 to Figure 3-10. Progression of tibiofemoral degeneration was the most significant mode of failure for this implant (see Table 3-8). Studies with pre- and post-operative functional outcomes showed significant improvements in all scores recorded.

Onlay, asymmetrical, anatomical designs

Prostheses: Natural Knee II (one study), Femoro Patella Vialla (three studies), Journey (one study)

The GRADE classification for this group was 'very low' due to reporting bias and omission of complication data. The majority of the studies were retrospective (four articles) compared with only one prospective study. The data available (Beitzel *et al.*, 2013; Mofidi *et al.*, 2012) consisted of small sample sizes with short follow-up and therefore little inference could be drawn. This problem was further perpetuated by the quality of reporting in some of the studies, for example, Beitzel *et al*. (2013) converted one knee to TKA but did not include this knee in the follow-up which was otherwise 100%. This illustration of reporting bias undermined the overall study findings. In addition, Beitzel *et al.* (2013) performed an a priori power analysis to show that the sample size was adequate. However, the point difference and standard deviation (S.D.) chosen were unnecessarily large, 25 points and S.D. 20 points and thus produced a very small sample size. Although the MCID for the Lysholm score has yet to be defined, previous studies have shown that a clinically detectable change in knee injuries is between 8.9 and 10.1 with a standard error range of 9.7 to 12.5 (Collins *et al.*, 2011). Unlike previous reports of high levels of aseptic loosening associated with FPV (Baker *et al.*, 2012), this complication was not found in this systematic review. This may have

been due to the short follow-up or because three out of five of the studies did not report complication data.

The onlay, asymmetrical, anatomical prostheses were designed to emulate the normal anatomical trochlea: asymmetrical 60:40 loading pattern on the trochlea between the lateral and medial facets of the patella, respectively. The Natural Knee II (Zimmer, Warsaw, Indiana, USA) is based on the NexGen TKA. The trochlear groove is recessed to reduce patellofemoral joint pressure and is designed to be compatible with an unresurfaced patella. The FPV lateral facet has a larger surface area and is relatively steeper than the medial facet. The sulcus angle is wider than in earlier prostheses (such as those in the ISN and IAN groups), measuring 140°, which is nearly as wide as the natural geometry at a mean of 145° (Shih *et al.*, 2004). The sagittal arc of curvature is 90°, which matches the distal femur. The FPV patellar component is sided and facetted with an off-centre longitudinal ridge that becomes increasingly more medialised from proximal to distal. Similar to the Natural Knee II, the Journey PFA, based on the GENESIS® II Total Knee System (Smith & Nephew (Reconstructive) Ltd, Memphis, USA), offers patellar resurfacing as optional because the trochlear component (oxidised zirconium) has a significantly lower coefficient of friction than cobalt chrome. Literature discussing the impact of design on outcome is not largely available on these newer prostheses. However, Mofidi *et al*. (2012) found the FPV, with its onlay design, restored patellofemoral

height rather than caused overstuffing; an argument used by the advocates of inlay prostheses.

Onlay, asymmetrical, patient-specific

Prostheses: Custom Performa Knee (one study), Kinematch (one study)

The GRADE rating for this category was ‘very low’. The main concern was the low number of patients and the quality of the data in the KineMatch study. This investigation was performed by the design team and therefore lacked independent assessment. In addition, no validated clinical outcomes were used and no complications were reported. A zero complication rate seems less plausible than the alternative explanations of missed complications due to infrequent patient follow-up and the exclusion of complications from reporting. The other investigation offered better quality research: independent study, survival and complication proportions were reported and a validated outcome was used to assess function (WOMAC score). The main limitations with this study were the pre- and post-operative functional outcome data were both collected post-operatively and the sample size was small.

The patient-specific prostheses were designed to overcome the limitations of size and lack of variability with off-the-shelf prostheses. Kinamed, the KineMatch® Patello-Femoral Replacement (Kinamed Inc.,

Camarillo, California) design utilises the patient's bony anatomy, identified using CT imaging, to determine the bony contact surface. When the bony anatomy is abnormal (e.g. trochlear dysplasia), the subchondral bone profile is used and the articular surface created to accommodate the domed patellar component. The Q angle and medial-lateral articular surface thickness are also patient-specific. The Custom Perform Knee (Biomet® Inc, Warsaw, Indiana) is an uncemented implant produced by similar methods. Despite the clear theoretical advantages of restoring an individual's patellofemoral anatomy, the data available in this group for analysis did not sufficiently prove superior in terms of survival, complications and clinical outcomes.

Mixed group

Prostheses: Richards I and II, CSF-Wright, Lubinus, Avon, FPV and miscellaneous other (not specified)

The purpose of including the mixed group was to determine whether there was a difference between this group and the single design groups. However, due to the level of evidence and heterogeneity of the data available, formal assessment (meta-analysis) was not possible.

The GRADE level of evidence was classified as 'low'. The main limitations in all three studies were retrospective data collection, no

comparator group and conclusions not supported by data presented. The strengths of the Arciero *et al*. (1988) study were the clear objectives stated and use of a relevant validated outcome. The main weakness was the authors concluded older patients with isolated patellofemoral arthritis have a high rate of success following PFA. The patient numbers were too low to accept this conclusion as truth rather than chance. Furthermore, there were many potential confounding factors, such as prosthesis used, concomitant surgery, patient activity, underlying diagnoses and other limb co-morbidities, which may have influenced this result. Mohammed *et al*. (2008) also concluded the FPV prosthesis was superior to the others assessed in the series, however, this was not sufficiently supported by the results. No attempt was made by the authors to demonstrate the patients that received the FPV were demographically the same as those that received the other prostheses. Despite this, this series had a large number of patients and involved multiple surgeons thus increasing the applicability of the data. Arnbjörnsson *et al*. (1998) reported the largest study in the group and involved multiple centres and surgeons. This study concluded that PFA was not as good as TKA although this was not assessed. Another weakness was the additional analyses of the Lysholm score in various subgroups: age, underlying diagnosis and pre index surgeries. Multiple analyses inevitably increase the risk of a Type I error.

Total knee arthroplasty

Prostheses: Anatomical Graduated Component (AGC), Legacy, Genesis, Low Contact Stress (LCS), Porous Coated Anatomic, Duracon, Insall-Burstein II, Press Fit Condylar (PFC), Total Condylar

The GRADE level of evidence for this group was 'low'. The strengths of the studies were clear study objectives and eligibility criteria and minimal loss to follow-up. However, there were general weaknesses such as retrospective data collection and lack of a PFA comparator group. Some studies restricted age to less than 60 years (Meding *et al*., 2007), others restricted selection to patients who had not undergone any pre index surgery procedures (Mont *et al*., 2002) and surgical interventions also varied from all receiving patellar resurfacing (Dalury, 2005) to no patellar resurfacing (Thompson *et al*., 2001). Parvizi *et al*. (2001) reported a number of complications related to prosthesis misalignment but no indication was given as to which of the three different prosthetic designs-posterior substituting, cruciate retaining and cruciate sacrificing were implicated. Thompson *et al*. (2001) did not use any validated outcomes to objectively assess patient function. In view of these general and individual study weaknesses the applicability of the findings were limited.

Comparison

Prostheses: Avon, Zimmer TKA and SIGMA

Only one comparative study was identified in this systematic review. The strengths of this study (Dahm *et al*., 2010) were no loss to follow-up, good data analysis, the authors reported validated scores pre- and post-operatively and attempted to match the groups of patients. They acknowledged the statistically significant difference in mean age and performed a multivariate regression analysis powered to >90% and stated it had no effect on the post-operative functional scores. However there were a number of limitations, the investigation was retrospective, the groups consisted of small sample sizes and the follow-up was relatively short. For these reasons the GRADE level was 'low'. In addition, although the groups were proven matched over a number of variables, the PFA group was a single surgeon series (except for two PFAs) and one prosthetic design (Avon) and the TKA group involved eight surgeons and two types of TKA design. Furthermore, this type of study design does not control for differences in unknown confounding factors between the groups.

3.8 Summary and Conclusion

This is the first systematic review to evaluate PFA by design features. Analysis of the primary outcome, survival proportions A and B, found non-anatomical inlay designs, ISN and IAN, produced the poorest results.

Though these inlay design groups had some of the longest follow-up, failures also occurred at shorter time points suggesting factors other than disease progression also contributed to the higher number of complications and revisions associated with these groups. The most common reason for failures was disease progression for all the groups. Early studies suggested patient selection should have been more rigorous, due to patients with evidence of primary/idiopathic arthritis or tibiofemoral degeneration undergoing a higher number of revisions (Argenson *et al*., 2005; de Winter *et al*., 2001; Smith *et al*., 2002). The proportion of failure related to disease progression was not always dependent on length of follow-up. For example, Board *et al*. (2004) reported 76% survival proportion A at 1.6 years mean follow-up. In contrast, the OSN group (Avon prosthesis), which had the largest number of studies, demonstrated survival proportion A range of 88% to 96% at 5.2 to 7.1 years mid-term follow-up. This group was the most comparable to the TKA group, which had a survival proportion range of 94% to 100% at 5.2 to 7.4 years mid-term follow-up. The lowest survival proportion B results were evident in the ISN and IAN groups. The ISN group (Richards prostheses) and the IAN group (Lubinus and Autocentric prostheses) were the earliest PFA designs and therefore subject to free-hand implantation methods, lack of appreciation for soft tissue balancing and less stringent patient selection.

The most common complication (in terms of proportion) was malpositioning/misalignment (most common in ISN, IAN and TKA groups)

followed by disease progression (most common in IAA and OSN groups) then ‘other’ (most common in OAP and mixed groups). Malpositioning/misalignment was recorded most frequently in the ISN and IAN groups. Persistent pain was a relatively common problem in the IAA and mixed groups and was the most common complication reported in the OAA group. Aseptic loosening and infection were a rare occurrence across all the groups. The number of reoperations was greatest in the ISN group; over 250 secondary surgical procedures (including revisions) were performed after the index surgery.

The functional outcome reporting varied considerably within and between the groups thus limiting the evaluation. Generally, when both pre- and post-operative outcome data was presented, improvements were seen and deemed significant in all the groups. Only one study in the mixed group (Arnbjörnsson & Ryd, 1998) found a poorer outcome in a patient post-operatively.

The applicability of the findings in this systematic review to the wider population was limited by a number of major weaknesses. Thirty-six out of forty studies were uncontrolled retrospective case series’ and overall the quality of evidence was rated as low or very low. The clinical heterogeneity within and between the groups was substantial. For example, some authors chose to restrict patients by age, aetiology, proven isolated disease and/or absence of antecedent surgery. Whereas others were more inclusive and performed PFA on any patient with symptomatic patellofemoral arthritis, including patients with asymptomatic

grade 2 or less tibiofemoral degeneration. The variation in follow-up time, sample size, number of studies evaluated in each design group, antecedent and concomitant surgery, patient activity levels prior to surgery, underlying diagnoses and other limb co-morbidities all limited the extent of the comparisons. Due to these known disparities it is impossible to determine the extent to which these factors influenced the survival and complication differences between the design groups compared to the effect of variation in prosthetic design.

The majority of the studies were subject to selection and reporting biases due to the retrospective (and on occasion non-consecutive) patient selection and data collection. The loss to follow-up varied considerably. For instance, 26% of the patients in the ISN group were lost to follow-up. Such high loses compromise the external validity of the results presented in this group.

The conclusions that can be drawn from this systematic review are limited due to the discussed limitations. The decision to only include published literature narrowed the potential inferences further due to publication bias. In addition, the understanding of patellofemoral arthritis has evolved over the decades and there is a greater appreciation for patient selection, soft tissue balancing, underlying alignment pathology and instrumentation improvements with the newer prostheses, all of which could have influenced outcomes more than prosthetic design. Whilst bearing in mind these drawbacks, the data indicate the inlay designs produced poor survival and high complication proportions and

the onlay symmetrical non-anatomical group was the most comparable to the TKA group.

In order to evaluate further survival and complication outcomes following PFA and TKA, a more robust study design that eliminates the issue of confounding factors, selection and reporting bias and focuses on comparing current PFA prostheses to TKA is required. A prospective randomised trial is the most rigorous way to determine the difference between PFA and TKA in terms of survival and complication. Whilst it is not feasible to compare each design group with TKA, a pragmatic randomised clinical trial comparing currently used PFA prostheses and TKA would address this question.

3.9 PRISMA Checklist

Section/topic	Item No	Checklist item	Reported in section
Title			
Title	1	Identify the report as a systematic review, meta-analysis, or both	Chapter 3
Abstract			
Structured summary	2	Provide a structured summary including, as applicable, background, objectives, data sources, study eligibility criteria, participants, interventions, study appraisal and synthesis methods, results, limitations, conclusions and implications of key findings, systematic review registration number	3.1
Introduction			
Rationale	3	Describe the rationale for the review in the context of what is already known	3.2
Objectives	4	Provide an explicit statement of questions being addressed with reference to participants, interventions, comparisons, outcomes, and study design (PICOS)	3.3
Methods			
Protocol and registration	5	Indicate if a review protocol exists, if and where it can be accessed (such as web address), and, if available, provide registration information including registration number	N/A
Eligibility criteria	6	Specify study characteristics (such as PICOS, length of follow-up) and report characteristics (such as years considered, language,	3.4

		publication status) used as criteria for eligibility, giving rationale	
Information sources	7	Describe all information sources (such as databases with dates of coverage, contact with study authors to identify additional studies) in the search and date last searched	3.5.1
Search	8	Present full electronic search strategy for at least one database, including any limits used, such that it could be repeated	3.5.2
Study selection	9	State the process for selecting studies (that is, screening, eligibility, included in systematic review, and, if applicable, included in the meta-analysis)	3.5.3
Data collection process	10	Describe method of data extraction from reports (such as piloted forms, independently, in duplicate) and any processes for obtaining and confirming data from investigators	3.5.3
Data items	11	List and define all variables for which data were sought (such as PICOS, funding sources) and any assumptions and simplifications made	3.4.4
Risk of bias in individual studies	12	Describe methods used for assessing risk of bias of individual studies (including specification of whether this was done at the study or outcome level), and how this information is to be used in any data synthesis	3.5.4
Summary measures	13	State the principal summary measures (such as risk ratio, difference in means).	3.5.5
Synthesis of results	14	Describe the methods of handling data and combining results of studies, if done, including measures of consistency (such as I2 statistic) for each meta-analysis	3.5.5
Risk of bias across studies	15	Specify any assessment of risk of bias that may affect the cumulative evidence (such as publication bias, selective reporting within studies)	3.5.4

Additional analyses	16	Describe methods of additional analyses (such as sensitivity or subgroup analyses, meta-regression), if done, indicating which were pre-specified	N/A
Results			
Study selection	17	Give numbers of studies screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally with a flow diagram	3.6.1
Study characteristics	18	For each study, present characteristics for which data were extracted (such as study size, PICOS, follow-up period) and provide the citations	3.6.3 Table 3-2 Table 3-3
Risk of bias within studies	19	Present data on risk of bias of each study and, if available, any outcome-level assessment (see item 12).	3.6.2
Results of individual studies	20	For all outcomes considered (benefits or harms), present for each study (a) simple summary data for each intervention group and (b) effect estimates and confidence intervals, ideally with a forest plot	3.6.4 3.6.5 3.6.6
Synthesis of results	21	Present results of each meta-analysis done, including confidence intervals and measures of consistency	N/A
Risk of bias across studies	22	Present results of any assessment of risk of bias across studies (see item 15)	3.6.2.6
Additional analysis	23	Give results of additional analyses, if done (such as sensitivity or subgroup analyses, meta-regression) (see item 16)	N/A
Discussion			
Summary of evidence	24	Summarise the main findings including the strength of evidence for each main outcome; consider their relevance to key groups (such as health care providers, users, and policy makers)	3.7
Limitations	25	Discuss limitations at study and outcome level (such as risk of bias), and at review level (such as incomplete retrieval of identified	3.8

		research, reporting bias)	
Conclusions	26	Provide a general interpretation of the results in the context of other evidence, and implications for future research	3.8
Funding			
Funding	27	Describe sources of funding for the systematic review and other support (such as supply of data) and role of funders for the systematic review	N/A

Chapter 4 The Warwick Patellofemoral Arthroplasty Trial: A Randomised Clinical Trial of Total Knee Arthroplasty versus Patellofemoral Arthroplasty in Patients with Severe Arthritis of the Patellofemoral Joint

4.1 Abstract

Objectives

Many surgeons believe total knee arthroplasty is the 'gold standard' treatment for all severe knee arthritis. However, patellofemoral arthroplasty has been recognised as a 'less invasive' procedure for the treatment of severe patellofemoral arthritis, preserving the tibiofemoral joint and cruciate ligaments, thus enabling a more rapid recovery. There are currently no published randomised clinical trials comparing these two interventions. The main objective of the current study was to determine whether there is a difference in functional knee scores and quality of life outcome assessments at one year post intervention between patellofemoral arthroplasty and total knee arthroplasty. The secondary objective was to assess the complication rates for both procedures.

Methods

Parallel, two-arm, double-blinded randomised clinical trial. This study was designed as a superiority trial. The sample size was determined using the functional section of the WOMAC score. Based on a two sample *t*-test (5%) using a minimal clinically important difference of 8 points and standard deviation of 10.8 points the number of participants required in each arm of the trial was 29. To allow for a 10% loss to follow-up, 32 patients were recruited in each arm. The study was powered at 80% to detect a difference at the 5% significance level. Skeletally mature patients, who were deemed suitable for patellofemoral arthroplasty by an

orthopaedic arthroplasty consultant and medically fit for surgery, were eligible for the trial. Consenting participants were randomised in a 1:1 allocation to either patellofemoral or total knee arthroplasty. The randomisation was computer generated and administered by a central independent randomisation centre. All participants had knee function, quality of life and physical activity assessed through the following outcomes. The primary outcome measure was the WOMAC (Western Ontario and McMaster Universities Osteoarthritis Index Score). The secondary outcome measures were OKS (Oxford Knee Score), AKSS (American Knee Society Score), EuroQol and UCLA Physical Activity Rating Scale and complication rates (related and unrelated serious adverse events). All participants were assessed using these outcomes following the initial trial participation consent (0 months). All baseline data was collected prior to randomisation. Subsequent data collection was carried out at 3, 6 and 12 months after the surgical intervention. All complications were recorded at each time point. The primary endpoint of the trial was 12 months. The intervention consisted of either patellofemoral arthroplasty or total knee arthroplasty. The surgical technique used was determined by surgeon preference. The participants and research associates remained blinded for the duration of the trial.

Results

Thirty-two patients were allocated to each treatment group. There were five protocol violations resulting in participants receiving treatment to

which they were not allocated (two in TKA group; three in PFA group). Three participants withdrew following allocated treatment and one declined treatment following allocation. These four participants formally withdrew from the trial and therefore were not included in the intention-to-treat analysis. A remainder of 60 participants completed the trial. On an intention-to-treat basis there were 31 participants in the PFA group and 29 in TKA group; per-protocol – 28 in PFA group and 27 in TKA group. No difference in participant demographics was identified. The complication rate was higher in the TKA group but numbers were small and no inferential statistics were performed. Endpoint (12 months) analyses showed no difference in functional outcomes, physical activity or quality of life between the treatment groups. The intention-to treat adjusted analysis estimated treatment difference for the WOMAC score was -3.31 with 95% CI (-14.34, 7.73) and p-value of 0.550, per- protocol was 0.0594 with 95% CI (-11.02, 11.14) and p-value of 0.991.

However, the adjusted 95% confidence interval for the treatment effect (intention-to-treat) on the WOMAC function score (-9.19, 6.80) confirms that an effect size of 8 points in favour of PFA cannot be rejected. The variability in the outcomes was greater than expected.

Conclusion

The results of this trial failed to show statistical evidence of a difference in treatment group outcome between TKA and PFA. Despite the trial being

underpowered the data does not support evidence for superiority of PFA over TKA. Therefore a non-inferiority trial involving a larger sample size across multiple centres is required.

4.2 Funding

Action Medical Research 01.05.09- 30.04.13

Grant Reference: AP1170

Amount: £91, 470

Grant title: A randomised clinical trial of total knee arthroplasty versus patellofemoral arthroplasty in patients with severe arthritis of the patellofemoral joint

The funders had no involvement or influence on the study design, conduct, analysis and reporting of the trial.

Annual interim reports were generated including the following information:

1. Background to the project and aims of the research
2. Details of work completed
3. Plan of work to be performed
4. Difficulties impeding project progression
5. Identified patentable or commercially exploitable aspects of the research
6. Publication details in full as result of the research

Annual lay reports for the public were generated including:

1. Progress
2. Anticipated outcomes
3. Likely benefits of the research

4.3 Trial Registration and Assignment Number

The assigned International Standard Randomised Controlled Trial Number (ISRCTN) is ISRCTN34863373. The trial formerly received notification of the assignment number on 2nd September 2009.

4.4 Intellectual Ownership

The original trial protocol and grant application was a joint effort of the trial team. Aspects of the trial that I conducted were:

1. Protocol background research and writing
2. Publication of trial protocol
3. Ethics Committee REC submission
4. Patient information sheets
5. GP information sheets
6. Patient recruitment
7. Data management: data collection on case report forms, database updates, recording of decision pending, missed, declined patients
8. Trial Management Group member
9. Ethics updates: submission of substantial changes
10. Submissions to Action Medical Research: application for no-cost grant extension, interim reports and final report

4.5 Introduction

Severe knee arthritis is a highly debilitating disease. According to the National Joint Registry, at the start of this trial in 2009 over 70,000 knee replacements were carried out over a year in the UK at an estimated cost of 280 million pounds. Currently, this value has since risen to over 90,000 replacements at a cost of nearly 400 million pounds (Wales, 2014). Isolated patellofemoral arthritis occurs in a number of patients diagnosed with severe arthritis. The radiological prevalence of this disorder is 13.6 to 24.3% in women and 11.0 to 15.4% in men over the age of 55 (McAlindon *et al.*, 1992). Current evidence no longer supports the use of arthroscopy or patellectomy for patients with severe isolated patellofemoral arthritis (Lennox *et al.*, 1994). Therefore, definitive treatment choice for patients is between patellofemoral arthroplasty and total knee arthroplasty.

While most surgeons believe total knee arthroplasty is the 'gold standard' procedure for all presentations of severe knee arthritis, patellofemoral arthroplasty offers potential advantages. This operation preserves the majority of the patient's own knee joint; minimal bone loss and retention of ligamentous stability. Patellofemoral arthroplasty has also been recognised as a less invasive operation, enabling a shorter recovery time (Ackroyd, 2005). Furthermore, the presentation and aetiology of patients with isolated patellofemoral arthritis tends to differ to those with tricompartmental disease and thus may justify the more targeted intervention offered by patellofemoral arthroplasty (Cicuttini *et*

al., 1997; Clark, 2008; Tamm *et al.*, 2008). Despite these theoretical advantages the initial designs did not produce acceptable results, mainly due to patellar misalignment, polyethylene wear and early failure due to disease progression (Arciero & Toomey, 1988). More recent studies have yielded more favourable results as demonstrated in Chapter 3. However, the inferences drawn from this systematic review did not provide sufficient evidence for deciding between total knee arthroplasty and patellofemoral arthroplasty; a randomised clinical trial is required.

4.6 Background

4.6.1 Rationale for Trial

There are currently no published results of randomised clinical trials comparing total knee arthroplasty and patellofemoral arthroplasty. One UK based trial had been registered (ISRCTN22478626) but not performed. Another trial is currently underway in Denmark. This trial consists of a comparison between two prostheses: Avon versus PFC, 50 participants per arm, 1:1 allocation. However, the results of this trial are yet to be established although the applicability of these findings may be limited to the prostheses used. Therefore, the question remains unanswered as to whether there is a functional difference in the outcome between total knee arthroplasty and patellofemoral arthroplasty. This deficit in the evidence is clearly demonstrated in chapter 3: systematic review, which showed the literature does not provide a satisfactory answer to the question. Furthermore, Arthritis UK have highlighted

research into joint replacement, in terms of survival, function and complication rates as a key research goal (UK, 2010). Therefore, the purpose of this trial was to address this shortfall in the literature, providing surgeons and patients with more robust and accurate information regarding knee function and complication rates.

4.7 Null Hypothesis

There is no difference in functional score (WOMAC- Western Ontario and McMaster Universities Osteoarthritis Index Score) at one year post-operation between total knee arthroplasty and patellofemoral arthroplasty.

4.8 Study Design

A two-arm, double-blinded, randomised clinical trial carried out in a single centre- University Hospitals Coventry and Warwickshire NHS Trust. The participants and research associates were blinded for the duration of the trial. The study was conducting in agreement with Good Clinical Practice (GCP) guidelines. All collaborators and research associates were GCP certified. The study was granted Ethical Approval by the Coventry Research Ethics Committee on 3rd March 2009 under the reference 09/H1210/9. Three subsequent substantial amendments were made to the trial once granted by the committee:

1. 8th April 2009: Addition of the UCLA knee rating scale; specifically the physical activity scale
2. 16th March 2011: The trial protocol was updated to comply with the University of Warwick Clinical Trials Unit Standard Operating

Procedure for ‘trial protocols’. Three small amendments were made to the methodology:

a. The randomisation sequence was held by the Clinical Trials Unit at the University of Warwick
b. The randomisation was no longer stratified by surgeon
c. No health economics analysis due to limited funding.

3. 20th June 2011: All patients that undergo arthroplasty surgery are routinely followed up at five-year intervals as part of standard clinical surveillance at University Hospitals Coventry and Warwickshire NHS Trust. In order to keep closer monitoring of the trial participants, permission for annual postal questionnaires (the same as the trial outcomes) was sought and granted. This was edited in the protocol and a new version (version 3) was submitted along with the annual review questionnaires. The trial protocol has been published; reference is as stated in Publications.

The research was carried out in compliance with the Helsinki Declaration.

4.9 Aims and Objectives

The aim of this randomised clinical trial was to determine whether a difference in functional outcome (WOMAC – Western Ontario and McMaster Universities Osteoarthritis Index Score) exists between TKA and PFA at one year post intervention.

There were two main objectives of this randomised clinical trial:

1. To quantify and draw inferences on observed differences in primary and secondary outcome measures between the trial treatment groups at one year post intervention.
2. To determine the complication rate of PFA versus TKA at one year post intervention.

4.10 Material and Methods

4.10.1 Eligibility Criteria

Inclusion Criteria: skeletally mature patients who were able to give informed consent, medically fit for an operation and had severe isolated patellofemoral arthritis deemed suitable for a PFA by their orthopaedic consultant were eligible for the trial. Severe disease was determined clinically and radiologically by the orthopaedic consultant in keeping with their standard practice. It was accepted that patients eligible for a PFA were also suitable for a TKA. These wide criteria meant that the results were readily generalisable to the varied population of patients with severe isolated patellofemoral arthritis. Exclusion criteria: included patients with tibiofemoral arthritis and those unfit for surgery. This was defined as the following:

1. Severe cardiac impairment e.g. heart or valve replacement, arrhythmia, previous severe myocardial infarction

2. Severe respiratory impairment e.g. chronic obstructive pulmonary disease, asthma that has required intensive care admission
3. Any other systemic medical condition that would prohibit administration of a general anaesthetic

Additionally, patients unable to adhere to trial procedures or complete questionnaires due lack of mental capacity (e.g. dementia) or intravenous drug abuse were excluded.

For patients who required contra-lateral knee arthroplasty during the duration of the trial, the second knee was not considered eligible for the study as the results of the second intervention would not have been independent of the first intervention.

4.10.2 Patient Selection

Patients were recruited from the orthopaedic clinics at University Hospitals Coventry and Warwickshire NHS Trust. Each arthroplasty clinic list was reviewed one to five days before the clinic date. All patients with patellofemoral pathology were brought to the attention of the orthopaedic consultant who then determined the patient's eligibility. Following identification of an eligible patient, the research associate, already present in clinic, was informed. The research associate provided the patient with a verbal explanation of what the trial entails and patient information sheet (see Appendix VII). The patients were given adequate time to discuss any aspects of the trial and raise queries with the research associate, their orthopaedic consultant, GP, family and friends.

This time frame was not restricted to allow ample opportunity for all issues to be addressed and for the patient to make an informed decision about participation in the trial.

4.10.3 Consent

Informed consent was obtained by the research associates. A system was set up to ensure any new information that emerged during the trial, which may have impacted participants' commitment to partake, was reviewed by the Trial Steering Committee.

All participants who decide to decline their treatment or withdraw post randomisation were followed up as normal in accordance with departmental guidelines. In the event these patients reconsidered their decision a signed updated consent form was required.

4.10.4 Trial Withdrawals

Participants were able to withdraw from the trial at any time without prejudice. When withdrawals occurred post randomisation, attempts were made to follow-up these patients and collect data as per protocol, until trial completion. The plan for this data was to include it in the primary intention-to-treat analysis and secondary per-protocol analysis. This strategy of follow-up and data collection also applied to those who did not receive treatment, with the intent of including their data in the intention-to-treat analysis.

4.10.5 Randomisation

The participants were randomised in a 1:1 allocation to TKA or PFA. The type of randomisation was simple, that is, not restricted, blocked or stratified. A secure centralised, telephone randomisation service provided the computer generated randomisation sequence. This service was based at the University of Warwick Clinical Trials Unit. An independent researcher contacted the service via telephone to establish the treatment allocation. This information was then emailed to the medical secretary of the operating consultant by the randomisation service. The medical secretary then entered the treatment allocation on the participants operation booking form but not on the operation list as to preserve concealment. This system ensured that the research associated collecting outcome data remained blind to the treatment allocation.

4.10.6 Blinding

The participants were also blinded to their treatment allocation to allow for an unbiased comparison to be made between the two interventions for the duration of the trial. To ensure participant blinding was not compromised, the participant GP, all ward staff including doctors, nurses, healthcare assistants, physiotherapists and theatre staff were informed of the trial protocol and therefore all necessary precaution was taken to avoid divulging the treatment allocation. The surgeons were, of course, not blinded and therefore did not partake in data collection.

4.10.7 Interventions

The two treatments in this study were patellofemoral arthroplasty (PFA) and total knee arthroplasty (TKA). Due to the pragmatic nature of the trial, the preferred prosthesis and preferred surgical technique was surgeon dependent. This decision was made in order to ensure the generalisability of the trial results to a broad group of patients and surgeons. All operations were carried out by or under the supervision of a consultant surgeon. Seven consultant orthopaedic surgeons, five registrars and two arthroplasty fellows were involved in performing the surgery. Each operation was either performed by or under the supervision of the consultant.

Patellofemoral Arthroplasty: During the trial the implants used were Avon, FPV, and Zimmer PFJ prostheses.

Total Knee Arthroplasty: During the trial the implants used were NexGen, Vanguard, Medial Pivot and Triathlon prostheses. Replacement of the patella was decided by the operating surgeon.

Rehabilitation: All patients received the same rehabilitation programme described in the departmental 'Knee Replacement: A Guide for Patients' Booklet'. This consisted of early exercises, specific precautions for the first three months, how to perform functional activities and advanced exercises.

4.10.8 Primary Outcome Measure

The key criteria for choosing the primary outcome measure were:

1. Meets standards for validity, reliability and responsiveness

2. Patient-reported
3. Tolerable questionnaire length to ensure maximum response and compliance
4. Widely-used to allow for comparability

One of the most commonly used assessment tools for patients with knee arthritis is the Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) (Angst *et al.*, 2001; Bellamy, 1995; Bellamy *et al.*, 1988; Bellamy *et al.*, 1990). This scale has been shown to be responsive (sensitive to change), valid for patients with arthritis (Kirkley *et al.*, 1999; Sun *et al.*, 1997; Theiler *et al.*, 1999) and user-friendly (Angst *et al.*, 2001).

The WOMAC score was chosen as the primary outcome. This patient reported outcome measure consists of 24 items (5 for pain, 2 for stiffness and 17 for physical function), all related to daily activities, which are directly impacted by poor function secondary to osteoarthritis. The best score achievable is 0 and the worst score is 96 (Bellamy *et al.*, 1988).

4.10.9 Secondary Outcome Measures

The choice of secondary outcome measures was based on identifying scores that potentially support the primary outcome and evaluate additional effects of the interventions. Scores that met closely the ideal criteria: validated, joint-specific and/or disease-specific and an effective measure over time, were considered. In addition, an appropriate

measure required for evaluating health economics was selected. Based on these requirements the following five secondary outcomes were chosen: Oxford Knee Score (OKS), American Knee Society Score (AKSS), EuroQol (EQ5D and EQ VAS), Disability Rating Index (DRI) and complications. Following receipt of ethics approval but prior to commencement of recruitment the UCLA Physical Activity Questionnaire (including walking and function ratings) was added as a substantial amendment in addition to the five existing outcomes. This outcome measure was added because it had been proven to be the most appropriate measure of activity for arthroplasty patients (Naal *et al.*, 2009).

The number of outcome measures used created high participant burden. In addition, there was significant overlap between some of the questionnaires. To encourage compliance, the decision was made via the appropriate channels (following proposal by Trial Management Group to the Trial Steering Committee) to exclude the Disability Rating Index (Salén *et al.*, 1994) from the collection of outcome measures. This outcome was chosen over the OKS and AKSS as these were deemed knee-specific and at the time, the EuroQol (EQ5D and EQ VAS) was kept as there was still a possibility of calculating health economics. The Trial Steering Committee were confident that the remaining outcome measures would capture sufficient information to answer the objectives outlined at the start of the project.

Therefore the final five secondary outcomes used in the trial were:

1. Oxford Knee Score (OKS): this patient reported outcome is a validated knee arthroplasty functional score consisting of 12 items related to daily tasks. The minimum (best outcome) score was originally described as 12 and the maximum (worst outcome) score, 60 (Dawson *et al.*, 1998). However, for this study the 0 to 48 method of scoring has been used, whereby 48 was considered the maximum and worst outcome.
2. American Knee Society Score (AKSS): this is also a validated knee function score, which consists of two parts: knee score and function score. Unlike the WOMAC and OKS, this outcome is not completely patient reported. The knee score involves assessment of pain, range of motion, stability and alignment. The function score includes assessment of daily activities to analysis functional capacity. Both scores range from 0 (worst outcome) to 100 (best outcome) (Insall *et al.*, 1989).
3. EuroQol (EQ5D): this patient reported validated health assessment consists of five 3-tiered questions related to daily activities and mental health. The combination of answers produces the quality of life score. The EQ Visual Analogue Scale (EQ VAS) is a patient reported health rating outcome on a 20cm vertical visual analogue scale. The scale ranges from 0 – worst imaginable health state and 100 – best imaginable health state.
4. UCLA Physical Activity Questionnaire: The University of California, Los Angeles activity rating scale is a patient reported assessment

on a 1 to 10 scale, whereby 1 is the worst outcome (no physical activity) and 10 is the best outcome (regular participation in impact sports) (Zahiri *et al.*, 1998). The walking and function rating aspect of the UCLA score are also calculated on the same scale.

5. Complications: all complications from time of intervention to completion of the trial were recorded.

4.10.10 Sample size

As stated above, previous work has suggested that the WOMAC score is the most sensitive condition-specific tool for assessing interventions in knee and hip osteoarthritis (Bellamy, 1995; Bellamy *et al.*, 1988). Angst *et al.,* (2001) successfullly demonstrated the use of the 17-item functional section of the WOMAC score to determine sample size.

Assuming the score follows a normal distribution, the required number of patients in each arm of the trial is 29, based on a two-sample *t*-test (5%) using a standard deviation of 10.8 points (Rooks *et al.*, 2006) and a minimum clinically important difference of 8 points, as shown in the calculation below (Rooks *et al.*, 2006). This number of patients will provide 80% power to detect a difference at the 5% level. To allow for a 10% loss to follow-up we will aim to recruit 32 patients in each arm.

The calculation was performed using PS Power and Sample Size Calculation Software version 2.1 30th February 2003 and further verified using a biostatistics reference as shown below (Chow *et al.*, 2008).

Calculations

Two arm trial; parallel groups

Calculation for Minimal Clinically Importance Difference (MCID):

Twelve percent of the absolute baseline value for the WOMAC functional score (68) equates to the MCID (Angst *et al.*, 2002; Angst *et al.*, 2001).

$$MCID = 68 \times 0.12$$
$$MCID = 8.16$$
$$\approx 8$$

Therefore, an 8 point difference was deemed clinically meaningful.

Calculation for Standard Deviation:

Effect size = mean of treatment group – mean of control group

standard deviation

therefore using mean difference of 8 points and effect size of 0.74 (Rooks *et al.*, 2006),

$$0.74 = \frac{8}{sd}$$

$$sd = \frac{8}{0.74}$$

$$sd = 10.8$$

Population standard deviation = 10.8 points WOMAC functional score

Calculation for Sample Size:

MCID = 8 points

Standard deviation = 10.8 points

Significance level = 5%

Power = 80%

$$n = \frac{2(Z_{\alpha/2} + Z_{\beta})^2 \delta^2}{\varepsilon^2}$$

$$Z_{\alpha/2} = 1.96$$
$$Z_{\beta} = 0.84$$
$$\delta^2 = 10.8^2$$
$$\varepsilon^2 = 8^2$$

$$n = \frac{2 \times 7.84 \times 116.64}{64}$$

$$n \approx 29$$

Accounting for a 10% loss,

$$n = \frac{29}{0.9}$$

$$n \approx 32$$

Therefore, 32 participants in each group.

4.10.11 Data Collection

For trial analysis, the primary time point for outcome results was at 12 months. In addition, data collection was performed at the planned time points: baseline (0 months), 3 months and 6 months post operation to allow for data monitoring and subsequent comparison analysis. At each time point the patients attended clinic and were reviewed by the research associate or fellow, and if necessary an orthopaedic surgeon. All the participants were reviewed by an orthopaedic surgeon at the standard 6 weeks follow-up appointment.

In order to minimise loss at recruitment, multiple contact addresses, telephone numbers and email addresses were collected. Considerable efforts were made by the trial team to keep in touch with patients. The target was for completion of follow-up for all 64 participants. Every possible effort was made to ensure loss to follow-up was kept at a minimum of no more than 10%. A system of reminders were introduced to ensure that return to clinic at three, six and twelve months was as complete as possible:

1. Research associate contacted the participant via telephone to make an appointment
2. If no response within two weeks a letter was sent out to the participant
3. If no response within two weeks the participant was contacted by telephone

4. If no response from the participant, the status of the participant was classified as a ‘non-responder’ and the case was closed.

In addition to this contingency plan, if loss to follow-up occurred at the 12 month time point, the plan was to inform the trial statistician so that the missing data could be determined using the interim scores.

4.10.12 Adverse Events Management

Adverse events (AEs) were defined as: *any untoward medical occurrence in a clinical trial subject and which does not necessarily have a causal relationship with the treatment*.

At each data collection time point the participants were asked whether they had experienced any adverse events since their last visit.

All AEs (excluding pre-planned procedures and pre-existing conditions) were listed on the appropriate Case Report Form and returned to the trial central office.

Serious adverse events (SAEs) were defined as any *untoward and unexpected medical occurrence that:*

1. *Resulted in death*,
2. *Life-threatening*
3. *Required hospitalisation or prolongation of existing inpatients´ hospitalisation*,
4. *Resulted in persistent or significant disability or incapacity*, *congenital anomaly or birth defect*

5. *Any other important medical condition, which, although not included in the above, required medical or surgical intervention to prevent one of the outcomes listed*.

SAEs that were expected as part of the surgical interventions and therefore did not require immediate reporting to REC were:

1. Related in general to surgery and anaesthetic:
    a. Chest Infection
    b. Urinary tract infection
    c. Myocardial infarction
    d. Stroke
2. Related to the arthroplasty surgery:
    a. Infection
    b. Delayed wound healing
    c. Bleeding
    d. Thromboembolic events
    e. Damage to nerves in the surgical area
    f. Damage to blood vessels in the surgical area

All SAEs were entered onto the SAE reporting form and given to the trial central office within 24 hours of the investigator becoming aware of them. Once received causality and expectedness were determined by the Chief Investigator, Professor Costa. As per trial protocol, if any SAEs were deemed unexpected and related to the trial, the main Research Ethics

Committee (REC) was notified within 15 days for a non-life-threatening event and within seven days for a life-threatening event. All such events were reported to the Trial Steering Committee and Data Monitoring Committee at their next meeting.

4.10.13 End of Trial

The end of the trial was defined as the final visit to the clinic of the last participant. This date was approximately 30.04.14.

4.10.14 Data Management

The Case Report Forms were designed by the trial coordinator in conjunction with the Chief Investigator and Statistician. All forms were filled out in the presence of the participant by the research associate (either myself as the research fellow or the research assistant). The forms were anonymised and securely stored; this was managed centrally by the trial coordinator.

4.10.14.1 Data Storage, Access and Quality Assurance

Personal data collected during the trial were handled and stored in accordance with the 1998 Data Protection Act.

All data collected was anonymised after the collection of baseline demographic data, and all participants were given a unique trial number. All electronic patient-identifiable information was held on a secure, password-protected database accessible only on university computers. All paper forms and trial records with patient-identifiable information were

stored in secure locked filing cabinets within a restricted access area of Warwick Medical School. Each participant's data was coded using the assigned unique trial number, linking the identifiable details to the outcome data. Access to both the database and stored identifiable information was restricted to authorised personnel.

Direct access to secure data and documentation was required for trial-related monitoring and auditing by Warwick Clinical Trials Unit (CTU). The retention of all paper and electronic data were authorised for a minimum of five years following completion of the trial.

The trial coordinator and research fellow monitored quality control by ensuring adherence to the trial protocol. Formal quality assurance checks were performed by Warwick CTU to ensure the integrity of randomisation, study entry procedures and data collection was upheld throughout the trial. A quality assurance manager performed annual inspections of the Trial Master File and provided recommendations where necessary. Written reports were provided to the REC at regular intervals during the trial.

Archiving of Trial Data

Data was handled in accordance with Warwick CTU guidelines and Standard Operating Procedures (SOPs).

4.10.14.2 Trial Oversight and Supervision

The day-to-day management of the trial was overseen by the Trial Coordinator and other members of the Trial Management Group (TMG), who met on a regular basis to assess trial progress.

The Trial Management Group consisted of:

1. Chief Investigator
2. Trial Coordinator
3. Trial Statistician
4. Two research associates (research fellow- myself and research assistant- research physiotherapist/nurse)

Independent oversight of the trial was carried out by the Trial Steering Committee (TSC).

The Trial Steering Committee consisted of:

1. Independent chair (Orthopaedic Consultant)
2. Independent member (Orthopaedic Consultant)
3. Chief Investigator (TMG representative)
4. Trial Coordinator (TMG representative)
5. Trial Statistician (TMG representative)
6. Research associate (TMG representative)

The four main objectives of the TSC were:

1. Monitoring and supervising the progress of the trial towards its interim and overall objectives. Ensured main trial objectives were not compromised and participants were protected from harm.
2. Reviewing at regular intervals relevant information from other sources
3. Consider the recommendations of the DMC, approve changes to the trial design, approve abstracts and manuscripts
4. Inform the funding body on the progress of the trial via annual report.

A Data Monitoring and Ethics Committee (DMC) was formed and consisted of:

1. Independent Chair (Orthopaedic Consultant with DMC experience)
2. Independent Clinical Expert (Orthopaedic Consultant)
3. Independent Statistician
4. Trial Statistician (attends DMC meeting as a non-voting TMG observer)

The DMC was independently chaired and established in accordance with the principles of Good Clinical Practice and the Warwick CTU SOPs. The three main objectives of the DMC were to:

1. Review data according to randomised treatment groups, at specific intervals, to ensure safe continuation of the trial. That is,

insufficient evidence of harm or benefit that would warrant stopping the trial

2. Review at regular intervals relevant information from other sources
3. Advise the TSC
4. Inform the funding body on the progress of the trial via interim progress report.
5. Formulation of a detailed statistical analysis plan (SAP).

4.10.14.2.1 Interim analyses

The detailed content of the interim analyses was identified following final data analysis for the purpose of complete reporting in this thesis. Prior to this, the meeting records remained confidential. Three interim analyses were performed throughout the duration of the trial. Interim reports were submitted to the funding body, AMR on the following dates: 14th May 2012, 20th June 2011 and 13th May 2010. The TSC was informed of all recommendations made in the report by the DMC.

In May 2010 the DMC reviewed the progress of the trial (12 months post-recruitment of first participant), specifically recruitment rate and complication rate. The complication rate was deemed within normal range and therefore not of concern. The recruitment rate was analysed and a decision was made to review the rate closely over the subsequent 6 months.

After twelve months of recruitment, it was established that the recruitment rate was lower than the target set at the beginning of the trial.

In the original trial application, it was predicted that 64 participants would be recruited in 20 months – 3.2 participants per month. However, the actual recruitment at this point was 2 participants per month, 67% of the target. Investigations were performed to determine why the rate was slower than expected.

The factors assessed were:

1. Number of eligible missed patients. This number was determined by checking theatre lists for patients who received patellofemoral arthroplasty but were not approached regarding trial participation. Three patients were identified. As a result of this loss of potential recruitment, a rolling programme of trial updates was issued to all staff to prevent this problem reoccurring.
2. Number of eligible patients who declined participation. Over the 12 month recruitment period 4 patients (15%) declined to enter the trial. This rate was expected, based on experience with similar trials within the research group.
3. Number of eligible patients referred to the trial centre. The fall in predicted numbers recruitable was likely due to a change in the referral pattern to the trial centre (University Hospitals Coventry and Warwickshire NHS Trust). Prior to the trial commencing, the majority of the patellofemoral arthroplasty operations for the Warwickshire region were provided by University Hospitals Coventry and Warwickshire NHS Trust. However, as

patellofemoral arthroplasty had gained popularity, the nearby district general hospitals started to also provide this operation as part of their arthroplasty service. Unfortunately, since this is a single centre trial, these patients could not be included in the study.

Based on this close monitoring, the DMC proposed that, if the same rate of recruitment were to continue, a 12 month extension was required in order to complete recruitment. The TSC was informed and the recommendation accepted. An application to the funders (Action Medical Research) was submitted for the project end date to be adjusted from 30.04.12 to 30.04.13. This requested was granted by Action Medical Research as a 'No-cost Grant Extension'. Additional finances were resourced from within the unit and from the support of the local Comprehensive Local Research Network (CLRN).

The final interim report in May 2012 confirmed completion of the trial recruitment. No further changes, requests or recommendations were made for the final year of recruitment.

In addition to the interim analysis of recruitment and complication rates, assessment of the outcome measures for both treatment groups was also evaluated by the DMC. Interim analyses of the primary and secondary outcome measures showed no evidence of a difference between the treatment groups, based on summary statistics and box plot analysis.

Since no evidence of clear benefit or harm was found to be associated with one treatment allocation the trial was continued to completion.

4.10.14.3 Statistical Analysis

A detailed SAP, constructed by the Trial Statistician, Dr Parsons, was agreed with the DMC at the beginning of the study.

Standard descriptive analyses were performed such as mean and standard deviation based on the normal distribution of the outcomes. Graphical representation of the data demonstrating correlation between the treatment groups was also produced for both primary and secondary outcome measures. Baseline data was summarised to check comparability between treatment arms, and to highlight any characteristic differences between those individuals in the study.

The main analysis was focused on determining differences in the primary outcome measure, the WOMAC score, between the two treatment groups on an intention-to-treat basis at 12 months post-operation. The significance in responses between treatment groups was assessed using an independent samples t-test; based on an assumed normal distribution for this outcome measure. Tests were two-sided and deemed to provide evidence for a significant difference if the *P* value was less than 0.05 (5% significance level). Estimates of treatment effects were presented with 95% confidence intervals. A linear regression analysis was also undertaken to assess the impact of participant age and gender. Selection of these covariates was made a priori based on previous knowledge of gender and age disparity. The primary analysis

was the adjusted analysis. Complication data were low for the various categories and therefore not appropriate for statistical analysis. Results from the unadjusted and adjusted analyses were presented graphically, together with diagnostic plots that illustrated trends and data distribution (that is, the underlying model assumptions). Missing data were not a problem experienced in this study and therefore the imputing methods described in the protocol to overcome missing data points were not required. The statistical analyses were carried out by the Trial Statistician, Dr Parsons, using R software (http://www.r-project.org/).

4.11 Results

No new information emerged during the trial that warranted communication with the trial participants. All three participants that withdrew were no longer willing to complete interim and primary end point outcomes. The one participant who declined treatment post randomisation also declined data collection. Therefore, these patients were not included in the primary intention-to-treat analysis or per-protocol analysis.

There were no unexpected or trial related SAEs that required REC notification.

The recruitment dates for the trial were 30.04.09 to 30.04.13. The follow-up time points were, as described in the methodology, 0, 3, 6 and 12 months. A total of ninety-four patients were screened for eligibility, that is, met the criteria for age, capacity to give consent and suitable for PFA. Of

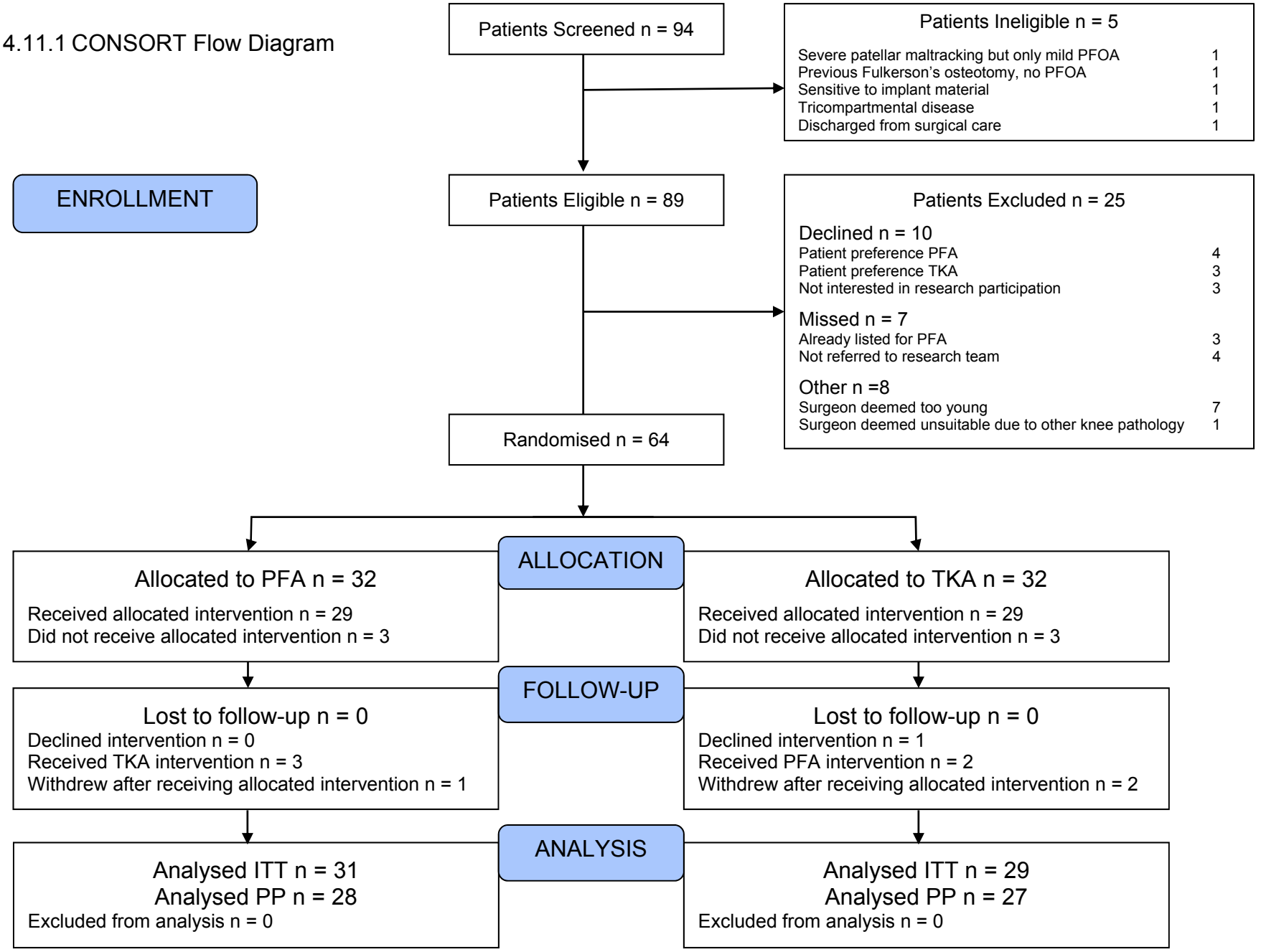
those patients, eighty-nine were deemed eligible in the first instance and five ineligible. The five that were not suitable had varying reasons not to undergo surgery (see section 4.11.1). Twenty-five patients were further excluded following consultation with the Orthopaedic Consultant or Research Associate. The most common reason was patient preference and surgeon concern regarding patient age. Out of the total of sixty-four patients recruited for the trial, three patients withdrew from further participation after receiving the allocated intervention and one patient declined surgery post allocation. The reasons for withdrawals were change of location for two participants and one found the commitment too burdensome. One participant no longer wanted surgery following randomisation and therefore declined further participation in the trial. The remaining sixty patients completed the study, although five patients did not receive their allocated treatment.

Table 4-2 highlights these five protocol violations. Three protocol violations involving participants assigned to PFA treatment receiving TKA intervention occurred because intraoperative assessment by the operating consultant identified tibiofemoral arthritis warranting TKA operative intervention. The two other protocol violations were participants assigned to TKA who actually received PFA intervention. Similarly, intraoperative assessment by the operating consultant deemed TKA unsuitable in cases where an isolated small trochlear lesion was identified and the patella appeared preserved; this occurred in three cases. None of

the five protocol violations were predictable based on clinical assessment or radiological evidence.

The CONSORT Flow Diagram (see section 4.11.1) demonstrates patient flow from screening to analysis. Table 4-1 and Table 4-2 show in more detail the participant numbers and status by allocation group and allocated intervention (intention-to-treat) and actual intervention received (per-protocol) for all trial participants, respectively.

4.11.1 CONSORT Flow Diagram



4.11.2 Tables and Graphs

Table 4-1 Trial participant numbers and status by allocated intervention group

Status	PFA	TKA	Total
Participant	31	29	60
Declined	0	1	1
Withdrawn	1	2	3
Total	32	32	64

Table 4-2 Allocated interventions (ITT) and actual interventions received (PP) for all trial participants who completed the study

		Per-protocol (PP)		
		PFA	**TKA**	**Total**
Intention-to-treat (ITT)	**PFA**	28•	3*	31
	TKA	2*	27•	29
	Total	30	30	60

*protocol violations
•number analysed per protocol

Table 4-3 demonstrated the participant demographics. There was no evidence of difference between the groups for any of the characteristics analysed.

Table 4-3 Participant Demographics

	PFA	TKA
Participants	n = 31	n = 29
Age (mean(±SD))	64.7 (±10.49)	64.4 (±12.84)
Gender (M : F)	9 : 22	3 : 26
Side (L : R)	15 : 16	18 : 11
BMI (kg/m^2)	28.9 (±6.72)	29.2 (±4.15)

Table 4-4 shows the mean and standard deviations of the primary outcome: WOMAC Score and secondary outcomes: American Knee Society Score (AKSS), Oxford Knee Score (OKS), UCLA rating scale and EQ5D QoL Score for the 60 participants analysed in this study at 4 time intervals: 0 months (baseline), 3 months, 6 months and 12 months. The

number of participants analysed at each time point, that is, *n*, for each outcome, is stated. Missing data was deemed very low therefore multiple imputation facilities were not used to impute data.

Table 4-4 Outcome Scores at 0 months (baseline), 3 months, 6 months and 12 months

Primary Outcome: WOMAC	PFA			TKA		
	n	Mean	SD	n	Mean	SD
Pain 0m	31	10.4	3.1	28	10.2	3.2
Pain 3m	29	5.7	4.2	24	7.2	4.6
Pain 6m	26	5.1	4.8	27	5.9	4.5
WOMAC Pain 12m	**29**	**6.0**	**4.7**	**25**	**4.7**	**3.8**
Stiffness 0m	31	4.7	1.6	28	4.5	1.6
Stiffness 3m	29	3.2	1.8	24	3.5	2.3
Stiffness 6m	26	2.7	2.0	27	3.2	2.2
WOMAC Stiffness 12m	**29**	**3.1**	**1.9**	**26**	**2.7**	**2.1**
Function 0m	31	36.3	12.0	28	36.3	10.6
Function 3m	29	21.5	16.4	24	25.5	15.9
Function 6m	26	20.9	16.1	27	21.1	15.6
WOMAC Function 12m	**29**	**21.9**	**15.7**	**26**	**20.2**	**12.7**
Total 0m	31	51.4	15.0	28	51.0	14.3
Total 3m	29	30.3	21.3	24	36.2	22.1
Total 6m	26	28.7	22.2	27	30.2	21.7
WOMAC 12m	**29**	**31.1**	**21.6**	**25**	**26.8**	**17.4**

Secondary Outcome: AKSS	PFA			TKA		
	n	Mean	SD	n	Mean	SD
Knee Score 0m	31	52.3	12.4	27	52.7	12.0
Knee Score 3m	29	75.4	17.2	23	65.0	20.3
Knee Score 6m	26	77.7	17.1	27	68.8	20.1
AKSS Knee Score 12m	**28**	**76.3**	**15.8**	**26**	**77.4**	**18.8**
Function Score 0m	31	53.7	16.4	28	57.5	18.2
Function Score 3m	29	66.5	23.2	23	66.7	20.2
Function Score 6m	26	72.9	20.4	27	68.0	21.9
AKSS Function Score 12m	**28**	**77.3**	**17.9**	**26**	**73.9**	**19.7**

Secondary Outcome: UCLA	PFA			TKA		
	n	Mean	SD	n	Mean	SD
Walking 0m	31	6.4	1.8	28	6.8	1.6
Walking 3m	29	7.7	2.1	24	6.9	2.4
Walking 6m	25	8.2	2.0	27	7.5	2.3
UCLA Walking 12m	**29**	**8.6**	**2.3**	**26**	**8.0**	**2.1**
Function 0m	31	5.0	1.6	28	5.4	1.9
Function 3m	29	6.7	2.8	24	6.5	2.2
Function 6m	25	7.4	2.2	27	7.1	2.6
UCLA Function 12m	**29**	**8.0**	**2.4**	**26**	**6.9**	**3.0**
Activity 0m	31	3.8	1.3	28	4.1	1.1
Activity 3m	29	4.7	1.3	24	4.4	1.3
Activity 6m	26	5.3	1.8	27	5.0	1.6
UCLA Activity 12m	**29**	**5.5**	**1.6**	**26**	**4.7**	**1.2**
Total 0m	31	17.8	4.5	28	18.8	4.4
Total 3m	29	25.3	6.2	24	23.3	7.1
Total 6m	26	27.0	7.6	28	24.7	9.3
UCLA 12m	**29**	**29.1**	**7.6**	**26**	**26.9**	**6.5**

Secondary Outcome: EQ5D	PFA			TKA		
	n	Mean	SD	n	Mean	SD
EQ5D 0m	31	0.4	0.3	28	0.4	0.3
EQ5D 3m	29	0.7	0.3	24	0.6	0.3
EQ5D 6m	23	0.8	0.3	26	0.7	0.3
EQ5D 12m	**29**	**0.8**	**0.3**	**25**	**0.7**	**0.2**

Secondary Outcome: OKS	PFA			TKA		
	n	Mean	SD	n	Mean	SD
OKS 0m	31	26.2	6.5	28	25.2	6.3
OKS 3m	28	15.6	9.0	24	17.5	9.5
OKS 6m	26	13.9	9.3	27	13.6	9.9
OKS 12m	**29**	**11.5**	**8.9**	**26**	**10.7**	**8.2**

WOMAC – Western Ontario and McMaster Osteoarthritis Index Score. Primary Outcome Measure blue borders. Patient reported 24 items (5 for pain, 2 for stiffness and 17 for physical function. 0 = best score, 96 = worst score; AKSS – American Knee Society Score. Function score patient reported. Function and Knee scores range from 1 to 100. 1 = worst score, 100 = best score; UCLA – University of California Los Angeles walking, function and activity scales. Patient reported. All scales range from 1 to 10. 1 = worst score, 10 = best score; EQ5D – EuroQol five-tiered questionnaire: mobility, self-care, usual activities, pain/discomfort, anxiety/depression. Patient reported. Quality of Life score. The scale ranges from -0.109 to 1.0. -0.109 = worst score, 1.0 = best score; OKS – Oxford Knee Score. Patient reported 12 items on knee function. Score ranges from 0 to 48. 0 = best score, 48 = worst score

The values in Table 4-4 have been represented graphically in the trend plots in Figure 4-1, which demonstrates the group means for the outcome scores, with 95% confidence intervals calculated using data from each assessment time point.

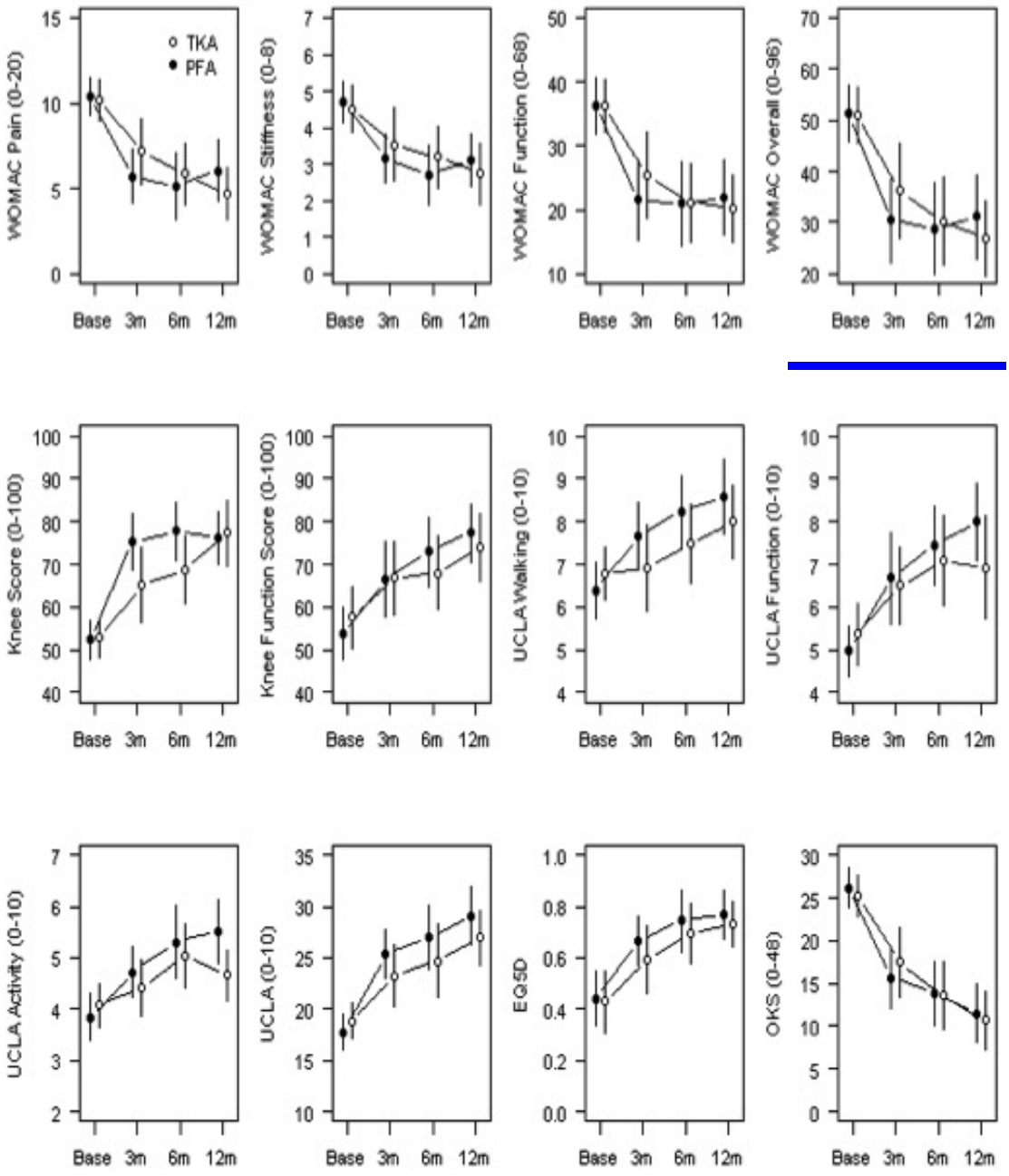


Figure 4-1 Trends in mean outcome scores by allocation group and time point

WOMAC – Western Ontario and McMaster Osteoarthritis Index Score. Primary Outcome Measure blue underline. Patient reported 24 items (5 for pain, 2 for stiffness and 17 for physical function. 0 = best score, 96 = worst score; AKSS – American Knee Society Score. Function score patient reported. Function and Knee scores range from 1 to 100. 1 = worst score, 100 = best score; UCLA – University of California Los Angeles walking, function and activity scales. Patient reported. All scales range from 1 to 10. 1 = worst score, 10 = best score; EQ5D – EuroQol five-tiered questionnaire: mobility, self-care, usual activities, pain/discomfort, anxiety/depression. Patient reported. Quality of Life score. The scale ranges from -0.109 to 1.0. -0.109 = worst score, 1.0 = best score; OKS – Oxford Knee Score. Patient reported 12 items on knee function. Score ranges from 0 to 48. 0 = best score, 48 = worse score

The primary endpoint for the clinical trial was the 12 months assessment. The primary and secondary outcome results are tabulated in Table 4-5; both the adjusted (in terms of age and gender) and unadjusted analyses are shown. Figure 4-2 is a series of box plots demonstrating the means, distribution of data and confidence intervals at 12 months for these outcome scores. All tabulated and graphically illustrated analyses were based on an ITT analysis except for Table 4-6, which shows the per-protocol analysis for the outcome scores at 12 months.

Table 4-5 Outcome Scores at 12 months following intervention, adjusted (age and gender) and unadjusted intention-to-treat analyses of intervention group differences

	TKA			PFA			Unadjusted Analysis			Adjusted Analysis		
	n	Mean	SD	n	Mean	SD	Δ†	95% CI	P value‡	Δ	95% CI	P value‡
WOMAC	25	26.80	17.38	29	31.07	21.63	-4.27	(-15.10, 6.56)	0.43	-3.31	(-14.34, 7.73)	0.55
WOMAC Pain	25	4.68	3.75	29	6.03	4.69	-1.35	(-3.70, 0.99)	0.25	-1.04	(-3.36, 1.28)	0.37
WOMAC Stiffness	26	2.73	2.05	29	3.10	1.88	-0.37	(-1.44, 0.69)	0.49	-0.37	(-1.47, 0.73)	0.50
WOMAC Function	26	20.15	12.70	29	21.93	15.68	-1.78	(-9.55, 5.99)	0.65	-1.20	(-9.19, 6.80)	0.77
AKSS Knee Score	26	77.35	18.83	28	76.25	15.83	1.10	(-8.38, 10.57)	0.82	-0.91	(-10.36, 8.53)	0.85
AKSS Function Score	26	73.85	19.66	28	77.32	17.87	-3.48	(-13.73, 6.77)	0.50	-3.33	(-13.96, 7.30)	0.53
UCLA Walking	26	8.00	2.12	29	8.59	2.32	-0.59	(-1.79, 0.62)	0.33	-0.51	(-1.78, 0.76)	0.43
UCLA Function	26	6.92	2.99	29	8.00	2.39	-1.08	(-2.54, 0.38)	0.14	-0.97	(-2.52, 0.57)	0.21
UCLA Activity	26	4.65	1.23	29	5.52	1.64	-0.86	(-1.66, -0.07)	0.03	-0.82	(-1.66, 0.02)	0.06
UCLA	26	26.92	6.50	29	29.10	7.59	-2.18	(-6.03, 1.67)	0.26	-2.05	(-6.14, 2.05)	0.32
EQ5D	25	0.73	0.21	29	0.77	0.25	-0.04	(-0.17, 0.09)	0.53	-0.06	(-0.20, 0.07)	0.34
EQ_VAS	25	76.36	21.82	29	72.86	22.31	3.50	(-8.60, 15.59)	0.56	1.49	(-11.11, 14.09)	0.81
OKS	26	10.65	8.23	29	11.48	8.89	-0.83	(-5.48, 3.82)	0.72	-1.11	(-6.03, 3.81)	0.65

Δ† unadjusted difference between means: TKA – PFA
Δ adjusted difference between means: TKA – PFA
‡ P values from independent samples t-test for unadjusted analysis and from linear regression including terms for age and gender in adjusted analysis

WOMAC – Western Ontario and McMaster Osteoarthritis Index Score. Primary Outcome Measure blue underline. Patient reported 24 items (5 for pain, 2 for stiffness and 17 for physical function. 0 = best score, 96 = worst score; AKSS – American Knee Society Score. Function score patient reported. Function and Knee scores range from 1 to 100. 1 = worst score, 100 = best score; UCLA – University of California Los Angeles walking, function and activity scales. Patient reported. All scales range from 1 to 10. 1 = worst score, 10 = best score; EQ5D – EuroQol five-tiered questionnaire: mobility, self-care, usual activities, pain/discomfort, anxiety/depression. Patient reported. Quality of Life score. The scale ranges from -0.109 to 1.0. -0.109 = worst score, 1.0 = best score; EQ VAS – EuroQol visual analogue scale. Patient reported. Range 0 to 100. 0 = worst imaginable health state, 100 = best imaginable health state; OKS – Oxford Knee Score. Patient reported 12 items on knee function. Score ranges from 0 to 48. 0 = best score, 48 = worst score

Table 4-6 Adjusted per-protocol analyses of intervention group differences at 12 months

	Δ	95% CI	P value‡
WOMAC	0.06	(-11.02, 11.14)	0.99
WOMAC Pain	-0.19	(-2.53, 2.15)	0.87
WOMAC Stiffness	-0.06	(-1.16, 1.05)	0.92
WOMAC Function	0.94	(-7.07, 8.94)	0.82
Knee Score	-2.73	(-12.16, 6.71)	0.56
Function Score	-7.44	(-17.92, 3.04)	0.16
UCLA Walking	-0.40	(-1.68, 0.87)	0.53
UCLA Function	-0.93	(-2.48, 0.63)	0.24
UCLA Activity	-0.84	(-1.68, -0.00)	0.05
UCLA	-2.10	(-6.2, 1.99)	0.31
EQ5D	-0.06	(-0.19, 0.08)	0.40
EQ_VAS	-1.76	(-14.38, 10.85)	0.78
OKS	0.66	(-4.27, 5.59)	0.79

Δ adjusted difference between means: TKA – PFA
‡ P values from linear regression including terms for age and gender in adjusted analysis

WOMAC – Western Ontario and McMaster Osteoarthritis Index Score. Primary Outcome Measure blue underline. Patient reported 24 items (5 for pain, 2 for stiffness and 17 for physical function. 0 = best score, 96 = worst score; AKSS – American Knee Society Score. Function score patient reported. Function and Knee scores range from 1 to 100. 1 = worst score, 100 = best score; UCLA – University of California Los Angeles walking, function and activity scales. Patient reported. All scales range from 1 to 10. 1 = worst score, 10 = best score; EQ5D – EuroQol five-tiered questionnaire: mobility, self-care, usual activities, pain/discomfort, anxiety/depression. Patient reported. Quality of Life score. The scale ranges from -0.109 to 1.0. -0.109 = worst score, 1.0 = best score; EQ VAS – EuroQol visual analogue scale. Patient reported. Range 0 to 100. 0 = worst imaginable health state, 100 = best imaginable health state; OKS – Oxford Knee Score. Patient reported 12 items on knee function. Score ranges from 0 to 48. 0 = best score, 48 = worst score

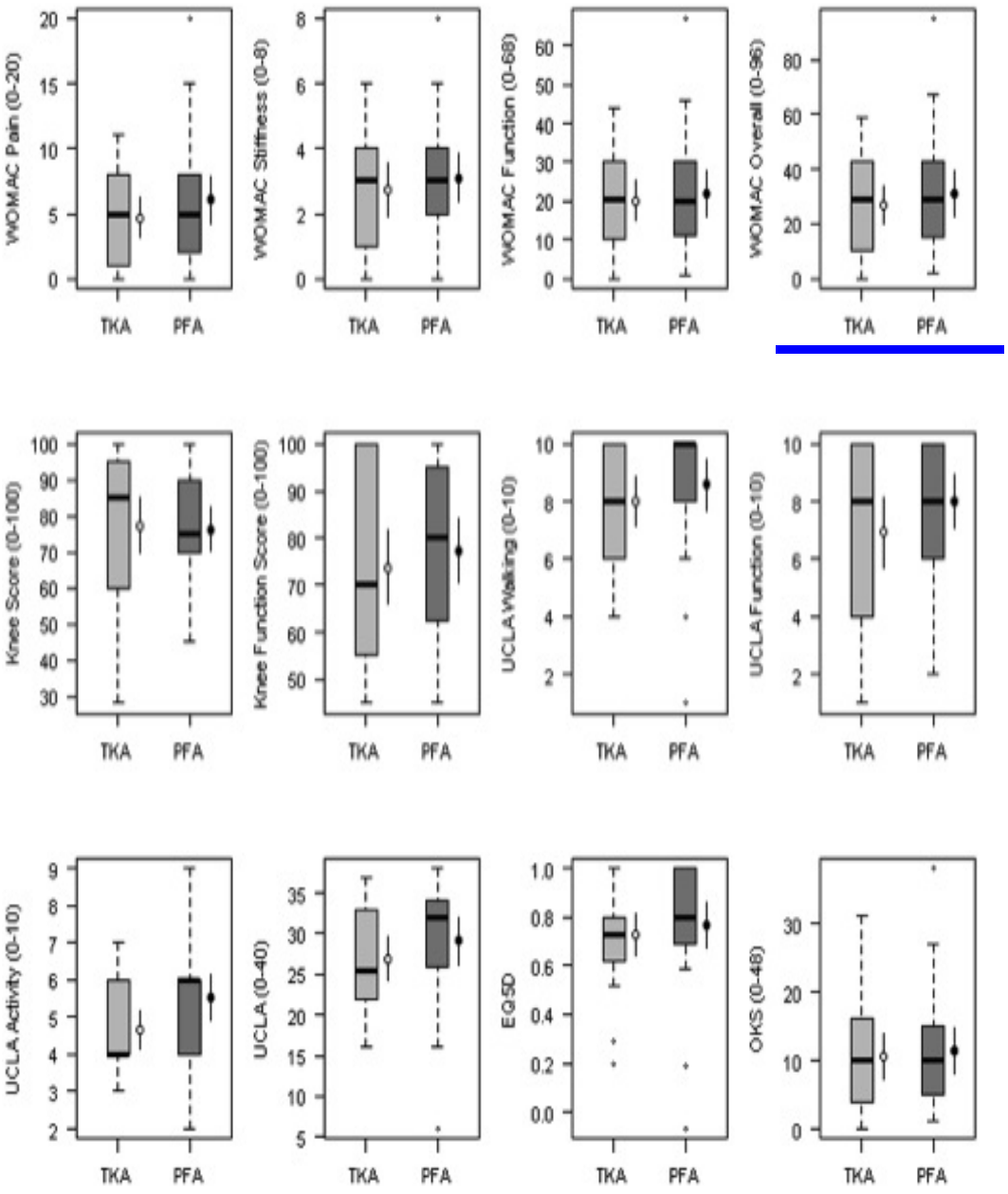


Figure 4-2 Boxplots illustrating means, data distribution and confidence intervals (95%) for the Outcome Scores at 12 months

WOMAC – Western Ontario and McMaster Osteoarthritis Index Score. Primary Outcome Measure blue underline. Patient reported 24 items (5 for pain, 2 for stiffness and 17 for physical function. 0 = best score, 96 = worst score; AKSS – American Knee Society Score. Function score patient reported. Function and Knee scores range from 1 to 100. 1 = worst score, 100 = best score; UCLA – University of California Los Angeles walking, function and activity scales. Patient reported. All scales range from 1 to 10. 1 = worst score, 10 = best score; EQ5D – EuroQol five-tiered questionnaire: mobility, self-care, usual activities, pain/discomfort, anxiety/depression. Patient reported. Quality of Life score. The scale ranges from -0.109 to 1.0. -0.109 = worst score, 1.0 = best score; OKS – Oxford Knee Score. Patient reported 12 items on knee function. Score ranges from 0 to 48. 0 = best score, 48 = worst score

Data on all complications that occurred during the intra-operative and post-operative periods were recorded. The details of these complications are summarised in Table 4-7.

Table 4-7 Complication Rates following interventions

Complications	No. of events in PFA group (n=31)	No. of events TKA group (n=29)
Deep infection	0	0
Deep vein thrombosis	0	1
Superficial wound complications	4	5
Revision	0	0
Further related procedures	0	4
Other	1	2
Total	5	15

All recorded SAEs reported are shown below in Table 4-8.

Table 4-8 Severe Adverse Events (SAEs)

SAE	PFA	TKA
Related in general to surgery and anaesthetic		
Chest infection	1	1
Related to arthroplasty surgery		
Deep infection	0	0
Superficial infection	4	5
Delayed wound healing	0	1
Thromboembolic event	0	1 (DVT)
Further surgery	0	2 (MUA; facetectomy)
Pain requiring aspiration/injection	0	2
Pain requiring admission for additional analgesia	0	1
Other		
Leg ulcer operated limb	0	2
Unrelated		
e.g. surgery, investigations	6	8
Total (related only)	**5**	**15**
Total (related and unrelated)	**11**	**23**

4.12 Results Analysis

The statistical analysis performed by the Trial Statistician was in agreement with the original statistical analysis plan (SAP) set out with the Data Management Committee (DMC) at the start of the study and as stated in section 4.10.14.3. No subsequent amendments were made to the SAP. All analysis was carried out using R (http://www.r-project.org/).

The principal analysis investigated differences in the primary outcome measure, the WOMAC score, between the two treatment groups (TKA and PFA) on an intention-to-treat (ITT) basis at 12 months post-operation. The difference in responses between treatment groups was formally assessed using an independent samples t-test; based on an assumed approximate normal distribution for this outcome measure. Tests were two-sided and considered to provide evidence for a significant difference if p-values were less than 0.05 (5% significance level). Estimates of treatment effects are presented with 95% confidence intervals. Linear regression analyses were also undertaken, incorporating terms that model the effects of patient age and gender in addition to the effects of the treatment groups (TKA and PFA).

There was no evidence that participant baseline demographics differed between treatment groups (see Table 4-3). A higher number of complications were reported in the TKA group. Although no deep infections were reported, the number of superficial infections requiring antibiotics was four and five in the PFA and TKA groups, respectively

(see Table 4-7 and Table 4-8). Four participants in the TKA group required further interventions: arthroscopic facetectomy (1), manipulation under anaesthesia (1) and aspiration/steroid injection (2); whilst there were no further interventions performed in the PFA group.

All outcome measures improved post intervention in both treatment groups, demonstrated graphically in Figure 4-1. Generally, the PFA group had better outcomes than the TKA group; although the difference was moderate (EQ-5D) to small (OKS). This is illustrated in the boxplots in Figure 4-2, which generally show higher medians and narrower confidence intervals for the PFA group. Interestingly, the overall WOMAC score and individual sub sections (pain, stiffness and function) were all higher at three and six months but at 12 months the reverse was true. It is possible that recovery during the initial rehabilitation period following PFA is relatively quicker than following TKA and this is reflected in the scores.

Statistically assessing the primary and secondary outcome measures at a significant level of 0.05, at the primary endpoint of the trial (12 months), on an intention-to-treat-basis, showed no statistical evidence of a difference between the two interventions. With the exception of the UCLA Activity Score (unadjusted analyses, see Table 4-5), both the unadjusted and adjusted analyses (adjustments made for age and gender using linear regression) showed no evidence of a significant clinical difference between the two treatment groups. Other than the UCLA Activity Score there were also no significant differences

found when the analyses were performed on the per-protocol allocation (see Table 4-6). This lack of difference is clearly demonstrated by the estimated treatment difference for the WOMAC score at 12 months, which was 0.0594 with 95% CI (-11.02, 11.14) and p-value of 0.991. In summary, the results of this trial failed to show statistical evidence of a difference in treatment group outcome between TKA and PFA.

However, the adjusted 95% confidence interval for the treatment effect (intention-to-treat) on the WOMAC function score (-9.19, 6.80) confirms that an effect size of 8 points in favour of PFA, which is the minimal clinically important difference (MCID) for this study, cannot be rejected. The variability in the outcomes was greater than anticipated (approximately 16 points rather than 10.8 points). Using the new estimate for the variability of the primary outcome measure, the minimum sample size for a definitive trial would be double the number used in this study, that is, 64 participants in each arm.

4.13 Discussion

This randomised clinical trial found no evidence of a difference in knee function between patients receiving patellofemoral arthroplasty versus total knee arthroplasty for severe isolated patellofemoral arthritis. However, clinically meaningful differences cannot be definitively ruled out based on these results and the long-term outcomes of current patellofemoral arthroplasty remains unknown.

Although the UCLA Activity Score (secondary outcome), showed evidence of a difference in activity levels 12 months after surgery, the

primary outcome and other secondary outcome scores failed to show a functional difference, despite all scores (except AKSS knee score) being consistently higher in the PFA group. The actual variance of the WOMAC was 1.5 times that anticipated, which therefore implies the study was underpowered to determine definitively whether a difference between the treatments truly exists.

Though the study results are inconclusive the methodology of the analysis was appropriate for the trial. The intention-to-treat analysis was based on the results from all the participants assigned to each treatment group, including the protocol violation cases. In addition to randomisation, this method of analysis offers the best assurance that the groups of participants being compared have similar characteristics, that is, unbiased comparison. It also best reflects the effects of the treatment in normal day-to-day clinical practice. Due to the number of protocol violations (5) and withdrawals/decline (4), the per protocol analysis was likely susceptible to attrition bias, which means the participant characteristics may no longer be similar between the groups. Per protocol analysis results generally provide less robust evidence however, in the absence of this form of bias this evidence is better at reflecting the effects of treatment than intention-to-treat analysis.

The overall rate of complications in the two groups was higher in the TKA group. The number of complications directly associated with arthroplasty was three times greater in the TKA group (12) compared with the PFA group (4). Although no statistical analysis was performed due to

the overall low number of complications, this factor is an important one that requires further exploration in a larger study. Complications have the potential to disrupt rehabilitation and therefore long-term functional outcome. This can limit the therapeutic benefits and profoundly affect the patient's quality of life. It is possible that if these findings are reproduced there may be cost effectiveness implications that favour PFA over TKA. This difference in complication rate was also observed by Dahm *et al*. (2010) who found, in a retrospective comparative study, a higher number of complications in the TKA group compared with the PFA group. In the current study, none of the participants suffered undue harm or complications that were life or limb threatening. All superficial wound infections were successfully treatment with oral antibiotics. Similarly, all patients received significant functional benefit from both interventions as demonstrated by the improvement in all clinical scores.

The pragmatic design of the study was to ensure maximum generalisability both in patient population and surgeon preferences hence the broad eligibility criteria and intervention described, respectively. Generalisability (external validity), defined as the extent to which the research findings can be applied to settings other than the one in which this study was performed, was limited. Due to the greater than anticipated variance of the primary outcome (WOMAC), the sample size was too small to definitively establish whether no difference exists between the two treatments despite the pragmatic nature of the design. In addition, the research setting for this study was in a large specialist centre and

therefore the result may not be applicable to patients in smaller district general hospitals. A single centre study allows for close monitoring and uniformity of trial procedures that reduce bias such as, blinding, outcome measurement and follow-up. Despite these advantages a single centre study offers less generalisable findings than a multicentre study due to the broader and larger surgeon and patient population.

Randomisation of the participants within the study ensured a sufficient degree of internal validity was achieved. Through the randomisation process, potential confounding factors (both known and unknown variables) were balanced between the treatment groups. Therefore, the increase in outcome measure scores post intervention can be interpreted as a direct result of the interventions received. The use of validated outcome measures, all of which measured the intended construct, ensured adequate construct validity.

To date, there are no published randomised clinical trials to compare with the findings of this study. Most recently, Dahm *et al*., (2010) published a retrospective, comparative two-year follow-up study and found patients in the PFA group had statistically significantly better AKSS, UCLA and Tegner scores compared with the TKA group. This study also showed that this difference was not dependent on the differences in age and presence/absence of trochlear dysplasia identified between the groups. Although useful, the generalisability of this study is limited by a number of weaknesses including small sample size, lack of randomisation, retrospective data acquisition and short follow-up.

There is currently one Danish multicentre randomised clinical trial comparing the Avon patellofemoral arthroplasty and the P.F.C. Sigma total knee arthroplasty. This trial consists of 50 participants in each arm with 1:1 allocation and the primary end point is five year data. The study is powered to 80% to detect a difference at the 5% level. At the time of writing the investigators are still recruiting. Five centres and seven surgeons are involved in the trial. Unlike the current study the surgical technique is very controlled. The chief investigator trained and assessed each trial operating surgeon before they performed solo surgery on trial participants. Another key difference is the decision to randomise, that is, whether the participant is suitable for a PFA, is made intraoperatively. The primary outcome measure is the Short Form 36 (SF-36) and secondary outcome measures are OKS, KOOS (Knee injury and Osteoarthritis Outcome Score), Kujala, EuroQol and 'satisfaction' questionnaire. The interim analysis, performed on patients recruited thus far (number unknown), showed significant differences in favour of PFA in all patient reported outcome measures at all time points up to 12 months. After one year, no difference between the treatment groups was identified. No difference in pain scores was seen at any time point. The loss to follow-up is minimal at present although six deaths have occurred in the PFA group; none in the TKA group. There is no indication to suggest these deaths were related to surgery.

The study design, in terms of randomisation and multicentre based increases the generalisability of the results. Intraoperative randomisation

minimises the potential number of protocol violations. The sample size, based on the Short Form 36 (SF-36), is larger than the sample in this current study and is thus more likely to be representative of the population from which the sample was drawn. The specifics of the inclusion criteria and full intervention details are not available therefore the generalisability with regards to these factors cannot be discussed. However, only two prostheses were used and one surgical technique thus the applicability of this data in terms of implant and surgical method is limited to those used in the trial. In the current study there was no restriction on the brand design of prostheses used or surgical technique. This pragmatic approach was taken to ensure generalisability therefore allowing conclusions to be drawn based on procedure type rather than implant design or surgical technique.

4.14 Limitations

The key limitations of this current trial were sample size, trial design in terms of test for superiority, single centre, the number of outcome measures used, number of protocol violations and recruitment rate. The former two limitations have already been addressed; the latter three will now be discussed.

The trial was designed to detect superiority of PFA over TKA. Even though the trial was not adequately powered, there is sufficient evidence to suggest it is highly unlikely that one treatment is superior or inferior over the other. For a future study it may be more appropriate to test for

non-inferiority. This is discussed in more detail in the following chapter of this thesis.

The number of outcome measures used was quite high. The impact of which was potentially two-fold: high patient burden and the increased risk of a positive result (less than 0.05 significant level) occurring due to chance being incorrectly interpreted as a difference between the treatment groups. Using a lower number of secondary outcome measures would have reduced the risk of a Type I error, that is, falsely rejecting the null hypothesis when it is true.

In total there were five protocol violations. Unforeseen tibiofemoral arthritis developing between diagnosis of isolated patellofemoral arthritis and timing of surgery, or undetected tibiofemoral arthritis is not common, as suggested by the 4.6% occurrence (three participants received TKA instead of PFA) seen in this trial. However, the other two protocol violations are harder to justify. Intraoperatively, it was identified two participants had small lesions, predominantly located on the trochlea. In each case the operating consultant chose to override the allocation and performed PFA instead of TKA. This highlights the difficulties that can occur with patient selection and thus surgeon agreement (equipoise). Had randomisation been performed intraoperatively, it is likely none of these protocol violations would have occurred.

Trial recruitment took longer than anticipated. Although this was mainly due to the change in referral of arthroplasty services, there were patients who declined participation. The patient's perception of the

difference between the interventions, in terms of the amount of joint replacement, could have influenced patient decision-making. No formal assessment of the quality of blinding was performed. If a participant became aware of their allocation this may have altered their responses to the outcomes evaluated. No formal qualitative research was performed as part of this trial to confirm either of these potential limitations.

4.15 Conclusion

The use of patellofemoral arthroplasty has rapidly increased over the last decade. The perceived advantages of this procedure are to preserve bone and restore the patellofemoral joint while maintaining native tibiofemoral knee kinematics. Previous studies have consisted mainly of retrospective case series' with varying results. More recent studies have produced results comparable with TKA. This literature does not sufficiently inform the debate regarding the true differences in clinical outcome between PFA and TKA in the treatment of severe isolated patellofemoral arthritis. Therefore, the aim of this study was to establish whether a difference in clinical outcomes exists between the two treatments.

This trial did not show evidence that patellofemoral arthroplasty provides improved knee function or increased activity levels, compared with total knee arthroplasty. However a difference cannot be excluded as previously discussed. The results of this study can be accepted as a pilot

trial. Through performing this study a number of factors on how to improve future studies have been learnt, such as, patient burden, recruitment rate, sample sizing and appropriate statistical trial testing. The patients in this trial will be reviewed in the coming years to establish the long-term outcomes although a larger, multicentre randomised clinical trial is required to establish whether PFA is not much worse than TKA. It is the long-term follow-up of these patients that will more accurately determine if there is any advantage with regard to the need for revision surgery. Despite this current study not showing any evidence to justify change in current practice, it did not identify any concerning reason why this procedure should only be performed in the context of a randomised clinical trial.

4.16 CONSORT Checklist

Table 4-9 CONSORT Checklist

Number	Section	Evidence Location
1a	Title: identification as randomised trial in the title	Chapter 4
1b	Abstract: structured summary of trial design, methods, results and conclusions	4.1
Introduction		
2a	Background: scientific background and explanation of rationale	4.6.1
2b	Objectives: specific objectives or hypotheses	4.9
Methods		
3a	Trial Design: description of trial design (e.g. parallel) including allocation ratio	4.8 4.10.5
3b	Changes to trial design: important changes to methods after trial commencement with reasons	4.10.9 4.10.14.2.1
4a	Participants: eligibility criteria for participants	4.10.1
4b	Study settings: settings and locations where the data were collected	4.10.2
5	Interventions: the interventions for each group with sufficient details to allow replication, including how and when they were actually administered/performed	4.10.7
6a	Outcomes: completely defined pre-specified primary and secondary outcome measures, including how and when they were assessed	4.10.8 4.10.9
6b	Changes to outcomes: any changes to trial outcomes after the trial commenced, with reasons	4.10.9
7a	Sample size: how sample size was determined	4.10.10
7b	Interim analyses and stopping guidelines: when applicable, explanation of any interim analyses and stopping guidelines	4.10.14.2.1
8a	Randomisation: sequence generation Method used to generate the random allocation sequence	4.10.5
8b	Randomisation: type Type of randomisation; details of any restriction (e.g. blocking and block size)	4.10.5
9	Randomisation: allocation concealment mechanism Method used to implement the random allocation sequence, describing any steps taken to conceal the sequence until interventions were assigned	4.10.5
10	Randomisation: implementation Who generated the allocation sequence, who enrolled participants, and who assigned participants to interventions	4.10.5
11a	Blinding: If done, who was blinded after assignment to interventions (e.g. participants, care providers, those assessing outcomes) and how	4.10.6
11b	Similarity of interventions: if relevant, description of the similarity of interventions	4.10.7
12a	Statistical methods: statistical methods used to	4.10.14.3

	compare groups for primary and secondary outcomes	
12b	Additional analyses: methods for additional analyses e.g. subgroup analyses and adjusted analyses	4.10.14.3
Results		
13a	Participant Flow: for each group, the number of participants who were randomly assigned, received intended treatment, and were analysed for the primary outcome	4.11.1
13b	Losses and exclusions: for each group, losses and exclusions after randomisation, together with reasons	4.11.1
14a	Recruitment: dates defining the periods of recruitment and follow-up	4.11
14b	Reason for stopped trial: why the trial ended or was stopped	4.10.13
15	Baseline data: a table showing baseline demographic and clinical characteristics for each group	4.11.2 Table 4-3
16	Number analysed: for each group, number of participants (denominator) included in each analysis and whether the analysis was by original assigned groups	4.11.2 Table 4-2
17a	Outcomes and estimation: for each primary and secondary. results for each group, and the estimated effect size and its precision (such as 95% confidence interval)	4.11.2
17b	Binary outcomes: for binary outcomes, presentation of both absolute and relative effect sizes is recommended	N/A
18	Ancillary analyses: results of any other analyses performed including subgroup analyses, distinguishing pre-specified from exploratory	N/A
19	Harms: all important harms or unintended effects in each group	4.11.2 Table 4-7 Table 4-8
Discussion		
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Chapter 5 Summary and Discussion

5.1 Introduction

The overall aim of this thesis was to add to the current knowledge regarding the use of arthroplasty treatment for severe isolated patellofemoral arthritis. The broad question addressed in this thesis was:

What are the differences in extensor mechanism efficiency, survival, number of complications and functional outcomes following TKA and PFA for the treatment of severe isolated patellofemoral arthritis?

Through attempting to answer this question, this mixed methods thesis has generated new knowledge that has further informed the debate between the choice of arthroplasty treatments and provided direction for future research.

This final chapter is divided into three sections:

1. Summary of Pre-existing Knowledge
2. Key Novel Conclusions
3. Limitations and Direction of Future Research

5.2 Summary of Pre-existing Knowledge

Previous literature on severe isolated patellofemoral arthritis has focused on the incidence and prevalence of this disorder, identifying a greater preponderance in females (Arendt, 2006; Dejour & Allain, 2004; Duncan *et al.*, 2006; McAlindon *et al.*, 1992; Mihalko *et al.*, 2007; Saleh *et al.*, 2005). Published knowledge on aetiological factors has highlighted patellar instability, specifically trochlear dysplasia, as an important risk factor for the development of patellofemoral arthritis (Dejour *et al.*, 2010; Mäenpää & Lehto, 1997b). Variations in Q angle have also been associated with progression of patellofemoral arthritis (Mihalko *et al.*, 2007). A systematic review on non-operative and operative management (van Jonbergen *et al.*, 2010a) found physiotherapy, taping and injections offered only short-term relief. Joint preservation procedures, such as total and partial patellectomy, arthroscopic debridement and tibial tubercle osteotomies were found to produce inconsistent outcomes and offer no long-term improvement; such findings were also demonstrated in earlier studies (Heatley *et al.*, 1986; Jenny *et al.*, 1996; Schepsis *et al.*, 1994). This review found outcomes following PFA (in selected patients) and TKA (with patellar resurfacing) were good but could not recommend one treatment over the other due to the weak methodological quality of the literature reviewed. This finding appears to reflect the general lack of consensus between the two arthroplasty choices. The majority of surgeons are aware of advantages of both arthroplasty treatments, some consider TKA the gold standard treatment because of the associated low

revision rate and good function (Dalury, 2005; Mont *et al.*, 2002; Thompson *et al.*, 2001), whereas others believe PFA preserves the tibiofemoral joint along with the native soft tissue constraints and is easier to revise to TKA, if required (Argenson *et al.*, 2005; Cartier *et al.*, 2005; Lonner *et al.*, 2006). A more recent meta-analysis (Dy *et al.*, 2012) compared the complications associated with PFA and TKA and concluded complications were more likely to occur following PFA compared with TKA and this association was thought to be related to prosthetic design. The main limitations with this investigation were: the weak methodological quality of the included studies and the subgroup analysis categorised by 'generation'. First and second 'generations' were the subgroups described in this study; the term 'generation' was stated to infer a difference in implant design. However, the first generation group included prostheses with considerable design variations ranging from inlay symmetrical non-anatomical to onlay asymmetrical anatomical prostheses. The quality of the meta-analysis was undermined by the high clinical heterogeneity. Furthermore, the authors' choice of analysis model (fixed or random) was based on the degree of heterogeneity calculated rather than establishing whether a common effect size exists between the studies for the specific variable of interest.

Until now, no systematic reviews have been performed assessing survival, complications and functional outcomes in terms of prosthetic

design and no randomised clinical trials had been performed to completion.

Current knowledge on the biomechanics of the native patellofemoral joint is well documented (Amis *et al.*, 2006; Amis & Farahmand, 1996; Christoforakis *et al.*, 2006; Farahmand *et al.*, 1998a; Farahmand *et al.*, 1998b; Feller *et al.*, 2007). The extensor mechanism is the primary support of the knee during standing and walking (Amis & Farahmand, 1996). Maintaining the integrity of the extensor mechanism following PFA and TKA is crucial for adequate performance of ADLs, such as rising from a chair, level walking and stair-climbing. Existing literature has investigated extensor mechanism function following TKA but not following PFA.

Quadriceps weakness following TKA is a well-reported problem. Studies have shown deficit in quadriceps strength in the short- and long-term following TKA (Berman *et al.*, 1991; Huang *et al.*, 1996). Reduced stride length and slowed walking and stair-climbing were demonstrated by Walsh *et al*. (1998) and Mizner and Snyder-Mackler (2005) as manifestations of this weakness. The effects of this strength deficit are likely influenced by prosthetic geometry.

Studies exploring the impact of prosthesis design on extensor mechanism function have focused on evidence of clinical difference between CR-TKA and PS-TKA. No studies have shown a difference in

functional validated outcomes. The literature tends to favour the notion of an increased range of motion associated with PS-TKA (Bercik *et al.*, 2013; Hirsch *et al.*, 1994). The size of the difference found in a recent meta-analysis (Bercik *et al.*, 2013) was not large and may therefore be of no clinical importance. Furthermore, a high degree of variation is associated with the commonest method used to measure this outcome (Trappler *et al.*, 2009).

The impact of prosthesis design on knee kinematics and biomechanics of the extensor mechanism has been investigated. The majority of the relevant literature has focused on the differences between CR-TKA and PS-TKA and femoral component condylar radii (multi-radius versus single). A number of studies have shown that the position of the tibiofemoral contact point in full knee extension is posterior to the mid-sagittal line in CR-TKAs compared to the native knee in which the tibiofemoral contact point is anterior to this line (D'Lima *et al.*, 2001; Dennis *et al.*, 1996; Stiehl *et al.*, 1995). During flexion the native knee demonstrates consistent posterior femoral rollback, in contrast, the CR-TKAs exhibits highly erratic anterior translation (Dennis *et al.*, 1996; Kim *et al.*, 1997; Stiehl *et al.*, 1995). PS-TKAs have not been shown to reproduce exact native knee kinematics although similarities have been demonstrated. In full extension the tibiofemoral contact position in PS-TKAs is anterior to the mid-sagittal plane but relatively posterior to the tibiofemoral contact position found in the native knee and femoral rollback has been shown to be abnormal, occurring to a significantly lesser degree

than in the native knee (Dennis *et al.*, 1996; Kim *et al.*, 1997). More recent studies have focused on attempting to recreate native posterior femoral rollback, which is thought to promote high knee flexion and to be a surrogate indicator for optimal extensor mechanism function (Fallahiarezoodar *et al.*, 2014). The theoretical value of posterior femoral rollback enhancing the extensor mechanism following PS-TKA compared to that occurring following CR-TKA has not been sufficiently demonstrated.

Investigations have been performed to determine whether there is a difference in extensor mechanism function associated with multi-radius femoral components compared with single radius femoral components. The results of the few studies assessing this generally varied depending on the cruciate design but no strong evidence exists in favour of one cruciate design. Literature that evaluated CR-TKAs found no kinematic difference between single radius and multi-radius femoral components on assessment of extensor mechanism function (D'Lima *et al.*, 2001; Hall *et al.*, 2008). However, Hall *et al*. (2008) did identify lower quadriceps tensile forces associated with the single radius components. In contrast, both studies evaluating PS-TKA reported single radius femoral component designs were more favourable than multi-radius in terms of extensor mechanism function (Gomez-Barrena *et al.*, 2010; Mahoney *et al.*, 2002). Overall no firm conclusions could be drawn due to various limitations associated with the studies, for example, confounding factors such as dissimilar surface geometry of femoral, tibial slope and polyethylene

insert components, retrospective comparison, inadequately matched groups, small sample size, use of unvalidated outcomes and risk of observer bias.

Until the performance of this biomechanics study, a direct comparison between PFA and TKA had not been performed in relation to extensor mechanism function.

5.3 Key Novel Findings and Conclusions

5.3.1 Biomechanics Study

This cadaveric study is the first investigation to date to assess the effect of PFA and TKA geometric differences on extensor mechanism efficiency, resultant force, peak pressure and contact area.

The key findings of this study were as follows:

1. Extensor Mechanism Efficiency (EME)
    a. The relationship between the knee flexion-extension cycle and extensor mechanism efficiency is bimodal: all four conditions (native knee, PFA, CR-TKA and PS-TKA) demonstrated a similar sinusoidal pattern of increasing EME between 0° and 50°, and a decreasing EME between 60° and 120°.

b. PFA produced the highest mean EME between 0° and 50°, peaking at 20° knee flexion. The greatest significant mean difference in this range was observed at 10° of knee flexion when compared with CR-TKA and PS-TKA.
c. PFA produced significantly greater EME than the native knee between 0° and 50° knee flexion. This may have been due to the increased offset lengthening the extensor moment arm beyond the native length.
d. In deep to mid flexion the EME was less efficient for all four conditions. PFA was generally lower than all the conditions and significant differences were detected between PFA compared with both native knee and CR-TKA at 80° knee flexion.
e. No significant difference in EME was found between CR-TKA and PS-TKA.

2. Patellofemoral Resultant Force
    a. No significant difference was detected between the three arthroplasty conditions at each angle of knee flexion tested, although the trend demonstrated higher forces were produced by PFA compared with CR-TKA and PS-TKA.
    b. The native knee produced significantly higher resultant force at 0° compared with CR-TKA and PS-TKA and at 30° knee flexion compared with all three arthroplasty conditions.

3. Peak Pressure
    a. The lowest peak pressures were produced by the native knee due to the elastic deformation of the articular cartilage, relative conformity of the native patellofemoral joint and the larger surface area.
    b. Peak pressures generated by PFA were significantly lower than CR-TKA and PS-TKA at 90° and 120° flexion due to the transition of the patellar button articulating with the native femoral condyle.
    c. All three arthroplasty conditions generated peak pressures four times that produced by the native knee at 0°.
    d. No difference in peak pressures was detected between CR-TKA and PS-TKA. These two arthroplasty conditions produced significantly greater peak pressures compared to PFA and native knee at each angle of knee flexion tested due to the hard bearing surfaces and non-congruent patellar component.

4. Contact Area
    a. The contact area was significantly higher for the native knee at all angles of knee flexion compared with all three arthroplasty conditions.
    b. The contact area results demonstrated an inverse relationship to the peak pressure. The contact area for PFA

increased markedly at 90° and 120° compared with values produced in early to mid flexion due to articulation of the patellar component with the native femoral condyle. The increase was significantly higher than the contact areas recorded for CR-TKA and PS-TKA.

c. No difference in contact area was detected between CR-TKA and PS-TKA.

Key Conclusions: The evidence showed PFA produced the greatest extensor mechanism efficiency between mid flexion and 0° extension when compared with the native knee, CR-TKA and PS-TKA. No difference was found between CR-TKA and PS-TKA to support previous reports of enhanced extensor function associated with the posterior stabilising design.

Applicability of the study findings to the clinical setting is limited. Rather, this study offers the benchmark methodology for future investigations involving simulation of activities of daily living whilst including hip, ankle and foot motion for more accurate interpretation.

5.3.2 Systematic Review

This systematic review evaluated PFA by design characteristics and TKA in terms of survival proportions and complications. The key findings were as follows:

1. Survival Proportion
    a. The survival proportion for the onlay symmetrical non-anatomical (OSN) design group was the most comparable to the TKA group. Similar mid-term follow-up survival proportions of the newer, onlay asymmetrical anatomical (OAA) designs have yet to be established.
    b. The non-anatomical designs: inlay symmetrical and inlay asymmetrical non-anatomical (ISN and IAN) designs produced the lowest survival proportions (A: revision to TKA for disease progression and B: any revision for any reason).
    c. Besides prosthetic design, free-hand bony cuts and implantation methods, lack of appreciation for soft-tissue balancing and less stringent patient selection would have also impacted survival proportion outcomes; the extent of influence of each factor remains unknown.

2. Complications
    a. The most common mode of failure (requiring revision surgery) was disease progression. The most common complications in order of frequency were: malpositioning/misalignment (ISN, IAN and TKA groups), disease progression (IAA and OSN groups) and ‘other’ (OAP and mixed groups).

b. Aseptic loosening and infection were rare occurrences in all the groups.
c. The number of reoperations was greatest in the ISN group.

Key Conclusion: This systematic review demonstrates the inlay non-anatomical designs produced the poorest outcomes in terms of survival and complication proportions. The OSN group was the most comparable to the TKA group. However, the extent to which other factors such as patient selection, soft tissue balancing, underlying alignment pathology and instrumentation developments influenced these outcomes cannot be determined from this study.

5.3.3 Randomised Clinical Trial

This randomised clinical trial is the first PFA versus TKA trial to be completed assessing functional knee scores, quality of life evaluations and complication rates. The key findings were as follows:

1. Functional and Quality of Life Outcomes
    a. This superiority trial did not find any evidence of a difference in knee function between patients receiving PFA versus TKA for severe isolated patellofemoral arthritis. The actual variance of the primary outcome (WOMAC) was considerably greater than that anticipated, therefore the

sample size was too small to determined definitively evidence of a difference between the two treatments.

b. The trial demonstrated both interventions provided all patients with a significant improvement in function and quality of life outcomes.

2. Complications

    a. The overall number of complications at one year follow-up was higher in the TKA group than the PFA group. None of the complications were life or limb threatening. Complications related specifically to the arthroplasty treatment were three times the number recorded in the PFA group although overall the numbers were low and therefore not analysed for statistical significance. A larger sample size would provide a more accurate representation of the complication rates associated with both interventions.

Key Conclusion: This trial showed no evidence that PFA provides improved knee function or increased activity levels, compared with TKA. However a difference cannot be excluded, as the study was underpowered. Although this trial did not generate new evidence to justify change in current practice, the data did not indicate superiority or inferiority of one intervention over the other, rather it highlighted the functional benefits of both interventions. A large, multicentre randomised

clinical trial is required to definitively establish whether these two interventions are comparable in terms of functional outcome.

5.4 Limitations and Directions for Future Research

Each study had limitations specific to the study design as discussed in detail at the end of each chapter. These limitations are summarised below along with potential future research.

5.4.1 Biomechanics Study

Summary of Limitations: The use of cadaveric knees offers an approximation of activity in the clinical setting therefore limiting applicability. The age of the specimen in terms of frozen period before use may have influence on the soft tissue integrity. The rig was a simplified design involving motion at the knee joint only, the influence of hip, ankle and foot motions, all of which impact activities such as walking and stair climbing, were not assessed. The flexion-extension cycle consisted of static measurements, which were used to assume the graphical model rather than exact data. Lack of hamstring loading may have influenced the extensor mechanism efficiency due to the risk of paradoxical anterior tibial translation, although prosthetic geometry and cruciate function have been proven to have a greater impact on extensor function. Inadvertent stretching of the soft tissues may have altered this

test constant between and within test condition trials. The sensors used to measure resultant force, peak pressure and contact area were sensitive to changes in temperature and humidity and degradation and physical damage (creasing) with increased use thus limiting the number of repetitions performed. The sensor calibration surfaces were flat and therefore not identical to the curvature of the patellofemoral joint test condition, which may have impacted the sensor interpretation.

Future Research: Despite the limitations of this study, the methodology and information gathered provides a platform from which more complex translational research can evolve. Assessing the extensor mechanism under more clinical conditions, such as stair climbing and walking, will further inform the debate. Achieving this would require building a modified Oxford Rig to simulate each segment of the lower limb (hip, ankle and knee motion) as close to normal as feasible. Continuous flexion-extension cycle could be achieved by using a Polaris Optical Tracking System with one optical tracker on the femur and one on the tibia. The angle between the femur and tibia would be computed in the sagittal plane perpendicular to the medial-lateral axis, using Visual 3D Motion. Once the experimental set up is built, the conditions tested in the current study can be repeated under physiological load to determine more accurately the impact of geometrical differences between PFA and TKA on extensor mechanism efficiency.

Another useful investigation aimed at determining which prosthesis offers the greatest mechanical advantage to the extensor mechanism: single radius CR-TKA or PS-TKA or multi-radius CR-TKA or PS-TKA could be performed using the same experimental set-up.

5.4.2 Systematic Review

Summary of Limitations: The majority of the studies were uncontrolled retrospective series and the quality of these studies was general rated as low in accordance with the GRADE assessment system. The degree of clinical heterogeneity within and between the groups was too high to perform a meaningful meta-analysis. Follow-up times, sample sizes, number of studies per design group, antecedent and concomitant surgery, patient activity levels prior to surgery, underlying diagnoses and other limb co-morbidities varied significantly thus limiting the extent of comparison and conclusions drawn related to prosthetic design influence. Selection and reporting biases were associated with the majority of the studies due to the retrospective nature of data collection and patient selection. High loss to follow-up affected a few groups, which would have undermined the external validity of the results reported.

Future Research: The execution of this systematic review was difficult due to the quality of the data and the inconsistencies in the outcomes reported. Performing further systematic reviews with the current data

available will not add to the current knowledge or resolve uncertainty due to the above weaknesses limiting applicability. In order to improve the quality of future studies that would be included in such systematic reviews, the use of Core Outcome Sets (COS) should ideally be adopted. Although, this methodology is currently being developed for trials, there is no reason why this cannot be extended to observational studies. The main advantage of utilising this system is that a set of outcomes or outcome measures and methods of measuring and reporting each outcome are standardised for the specific area of research. This enables the data from each study to be synthesised, compared and contrasted sufficiently, which ultimately leads to more decisive conclusions being drawn and more informed choices for surgeons and patients. If all future studies involving patellofemoral arthroplasty adopted the use of COS and trials followed the Core Outcome Measures in Effective Trials (COMETS) Initiative this will increase the impact and quality of the research produced.

5.4.3 Randomised Clinical Trial

Summary of Limitations: This trial was relatively small and performed by a single centre, both factors reduce the generalisability. The anticipated variance of the primary outcome was much lower than the actual variance calculated, rendering the sample size inadequate. A large number of outcome measures were used, which increased participant burden and the risk of a Type I error. Patient perception of the differences between

the interventions was not formally assessed and no formal evaluation of the effectiveness of participant blinding was carried out. Therefore the impact of a participant becoming aware of the intervention they received on outcome assessment was unknown. The use of qualitative research to determine patient perception at the point of recruitment and following receipt of intervention may have enhanced the quality of this trial. There were five protocol violations of which the majority were likely due to a lack of equipoise. Intraoperative randomisation may have minimised the number of violations. The trial was designed to test superiority but the data indicates one treatment is unlikely to be superior to the other; therefore a test of non-inferiority would have been more appropriate. No cost-effectiveness analysis was performed; such an analysis is particularly useful when no clear functional advantage in favour of one intervention has been established.

Further research: The pilot trial provided very useful information for devising a larger, multi-centre trial. The most useful evidence was that non significant differences in outcomes between the interventions were detected, thus countering the assertion that PFA is superior to TKA. Therefore, rather than employing a statistical analysis to detect superiority, the aim for this proposed clinical trial is to test for non-inferiority. A non-inferiority trial test would aim to show PFA treatment (the experimental treatment) is no worse than TKA (the standard treatment). There are a few reasons why this is the more suitable test to

apply: PFA is unlikely to be significantly better than TKA on primary outcome such as function/efficacy but is likely to be better on secondary outcomes such as implant costs and short to mid-term complication rates. Another factor in favour of PFA is the maintenance of more normal knee kinematics due to preservation of the tibiofemoral joint and cruciate ligaments and the relative ease of revision surgery to TKA.

The statistical methodology for a non-inferiority test only requires defining the anticipated upper bound mean difference in effect between the PFA (experimental) and TKA (standard) treatments: Δ_{NI}. This in practice is a one-sided test with a significance level of 0.025, whereby a significant result ($p < 0.025$) means PFA is not (much) worse than TKA, determined by the chosen value for Δ_{NI}. Determining the non-inferiority boundary is challenging as it requires the chosen outcome score to be consistently greater in the TKA group than the PFA group but by a specific meaningful amount, that is, the minimum important difference (MID). Therefore, the precision of the outcome tool must be known. Using a patient reported outcome with robust evidence for the MID will be the most appropriate method in order for the trial to exhibit non-inferiority. The choice of outcome is also crucial because the non-inferiority boundary influences the sample size. Undoubtedly, using this trial test, especially with the one sided alpha, will increase the sample size significantly in comparison to that calculated for the pilot study, therefore the study will have to be multi-centre. The advantage of this is two-fold: the recruitment time will be within a realistic time frame and the more trial

sites are involved, the greater the generalisability to the broader NHS clinical setting.

The trial sites should consist of a range of hospitals to represent the wider orthopaedic community, including experienced and less experienced surgeons in terms of PFA intervention. Although a minimum level of experience will be required. Surgeon equipoise is also another important factor to consider and establish in each trial site. In the pilot study two out of five of the protocol violations were related to this issue. Intra-operative randomisation may reduce the occurrence of such violations.

Cost-effectiveness data collection, specifically for cost-utility analysis would be useful in determining the benefit of the interventions in terms of the number of years lived in full health by the trial participants (quality adjusted life years (QALYS)). Using QALYS to compare the interventions allows for a more complete comparison rather than the monetary comparison offered by a simple cost-benefit analysis. There are some pitfalls to performing cost-effectiveness analysis, which must be taken into consideration. The analysis is based on the trial results and therefore limited by the quality of the data. If the trial is biased, the same will be true for the cost-effectiveness analysis. The time horizon for the cost-effectiveness analysis may be 10 to 20 years and therefore beyond that which is feasible or intended for clinical data collection. Long-term modelling of this outcome rather than direct measurement would be required.

Another additional area for research alongside the trial is the use of qualitative methods to assess patient perception. Patient perception of the treatments may influence the decision to participate. Identifying the differences in the populations that chose to participate compared to those that decline may establish areas for development in recruiting style and approach. Participants with a preference for one intervention may influence outcome results, particularly if they become aware of the intervention received. The importance of knowing how participants react, that is, modification to their behaviour or approach to rehabilitation will further add to the knowledge gained from performing this trial.

The ultimate aim of this research is to further inform the debate regarding choice of treatment between PFA and TKA for isolated patellofemoral arthritis. Therefore, it is important to continue developing new research ideas which may, in time, result in a definitive answer being established.

Chapter 6 Appendices

Appendix I: Extensor Mechanism Efficiency Data for Each Individual Knee

Table 6-1 Knee MO1 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	137.25	85.52130687	0.25	21.38032672	205	0.104294277
110	0.623106061	103	64.17992428	0.25	16.04498107	205	0.0782682
100	0.623106061	99.5	61.99905307	0.25	15.49976327	205	0.075608601
90	0.623106061	104.75	65.27035989	0.25	16.31758997	205	0.079598
80	0.623106061	111	69.16477277	0.25	17.29119319	205	0.084347284
70	0.623106061	117	72.90340914	0.25	18.22585228	205	0.088906597
60	0.623106061	130.25	81.15956445	0.25	20.28989111	205	0.098975079
50	0.623106061	144.5	90.03882581	0.25	22.50970645	205	0.109803446
40	0.623106061	162	100.9431819	0.25	25.23579547	205	0.123101441
30	0.623106061	168	104.6818182	0.25	26.17045456	205	0.127660754
20	0.623106061	164.5	102.500947	0.25	25.62523676	205	0.125001155
10	0.623106061	152	94.71212127	0.25	23.67803032	205	0.115502587
0	0.623106061	39.25	24.45691289	0.25	6.114228224	205	0.029825504

Table 6-2 Knee MO1 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	173	107.7973486	0.25	26.94933714	205	0.131460181
110	0.623106061	108.25	67.4512311	0.25	16.86280778	205	0.082257599
100	0.623106061	76.5	47.66761367	0.25	11.91690342	205	0.058131236
90	0.623106061	68.5	42.68276518	0.25	10.67069129	205	0.052052153
80	0.623106061	97	60.44128792	0.25	15.11032198	205	0.073708888
70	0.623106061	118.25	73.68229171	0.25	18.42057293	205	0.089856453
60	0.623106061	138.75	86.45596596	0.25	21.61399149	205	0.105434105
50	0.623106061	169.25	105.4607008	0.25	26.36517521	205	0.128610611
40	0.623106061	176.75	110.1339963	0.25	27.53349907	205	0.134309752
30	0.623106061	172.25	107.330019	0.25	26.83250475	205	0.130890267
20	0.623106061	152.25	94.86789779	0.25	23.71697445	205	0.115692558
10	0.623106061	119	74.14962126	0.25	18.53740531	205	0.090426367
0	0.623106061	15.5	9.658143946	0.25	2.414535986	205	0.011778224

Table 6-3 Knee MO1 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	153.5	95.64678036	0.25	23.91169509	205	0.116642415
110	0.623106061	97.25	60.59706443	0.25	15.14926611	205	0.073898859
100	0.623106061	92.25	57.48153413	0.25	14.37038353	205	0.070099432
90	0.623106061	99.75	62.15482958	0.25	15.5387074	205	0.075798573
80	0.623106061	91	56.70265155	0.25	14.17566289	205	0.069149575
70	0.623106061	96.5	60.12973489	0.25	15.03243372	205	0.073328945
60	0.623106061	112.25	69.94365535	0.25	17.48591384	205	0.085297141
50	0.623106061	113.75	70.87831444	0.25	17.71957861	205	0.086436969
40	0.623106061	156.25	97.36032203	0.25	24.34008051	205	0.1187321
30	0.623106061	133.75	83.34043566	0.25	20.83510891	205	0.101634678
20	0.623106061	135	84.11931824	0.25	21.02982956	205	0.102584534

10	0.623106061	103.5	64.49147731	0.25	16.12286933	205	0.078648143
0	0.623106061	30	18.69318183	0.25	4.673295458	205	0.022796563

Table 6-4 Knee MO1 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	151.5	94.40056824	0.25	23.60014206	205	0.115122644
110	0.623106061	116	72.28030308	0.25	18.07007577	205	0.088146711
100	0.623106061	105.5	65.73768944	0.25	16.43442236	205	0.080167914
90	0.623106061	99.25	61.84327655	0.25	15.46081914	205	0.07541863
80	0.623106061	90	56.07954549	0.25	14.01988637	205	0.06838969
70	0.623106061	93.75	58.41619322	0.25	14.6040483	205	0.07123926
60	0.623106061	100.75	62.77793565	0.25	15.69448391	205	0.076558458
50	0.623106061	102.5	63.86837125	0.25	15.96709281	205	0.077888258
40	0.623106061	106.5	66.3607955	0.25	16.59019887	205	0.080927799
30	0.623106061	124.75	77.73248111	0.25	19.43312028	205	0.094795709
20	0.623106061	139	86.61174248	0.25	21.65293562	205	0.105624076
10	0.623106061	88.5	55.1448864	0.25	13.7862216	205	0.067249861
0	0.623106061	30.75	19.16051138	0.25	4.790127844	205	0.023366477

Table 6-5 Knee MO2 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	126	78.51136369	0.25	19.62784092	205	0.095745565
110	0.623106061	103.5	64.49147731	0.25	16.12286933	205	0.078648143
100	0.623106061	103.25	64.3357008	0.25	16.0839252	205	0.078458172
90	0.623106061	101.5	63.24526519	0.25	15.8113163	205	0.077128372
80	0.623106061	109.75	68.38589019	0.25	17.09647255	205	0.083397427
70	0.623106061	119	74.14962126	0.25	18.53740531	205	0.090426367
60	0.623106061	134.75	83.96354172	0.25	20.99088543	205	0.102394563

50	0.623106061	147	91.59659097	0.25	22.89914774	205	0.11170316
40	0.623106061	154	95.95833339	0.25	23.98958335	205	0.117022358
30	0.623106061	157.5	98.13920461	0.25	24.53480115	205	0.119681957
20	0.623106061	162.75	101.4105114	0.25	25.35262786	205	0.123671355
10	0.623106061	134.75	83.96354172	0.25	20.99088543	205	0.102394563
0	0.623106061	34.75	21.65293562	0.25	5.413233905	205	0.026406019

Table 6-6 Knee MO2 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	149.5	93.15435612	0.25	23.28858903	205	0.113602873
110	0.623106061	92.5	57.63731064	0.25	14.40932766	205	0.070289403
100	0.623106061	84.75	52.80823867	0.25	13.20205967	205	0.064400291
90	0.623106061	78	48.60227276	0.25	12.15056819	205	0.059271064
80	0.623106061	50.75	31.6226326	0.25	7.905658149	205	0.038564186
70	0.623106061	82.75	51.56202655	0.25	12.89050664	205	0.06288052
60	0.623106061	121.75	75.86316293	0.25	18.96579073	205	0.092516052
50	0.623106061	162	100.9431819	0.25	25.23579547	205	0.123101441
40	0.623106061	192.25	119.7921402	0.25	29.94803506	205	0.146087976
30	0.623106061	201.5	125.5558713	0.25	31.38896782	205	0.153116916
20	0.623106061	198.25	123.5307766	0.25	30.88269415	205	0.150647289
10	0.623106061	178.5	111.2244319	0.25	27.80610797	205	0.135639551
0	0.623106061	116.5	72.59185611	0.25	18.14796403	205	0.088526654

Table 6-7 Knee MO2 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	123.5	76.95359853	0.25	19.23839963	205	0.093845852
110	0.623106061	118	73.5265152	0.25	18.3816288	205	0.089666482
100	0.623106061	114.75	71.5014205	0.25	17.87535512	205	0.087196854

90	0.623106061	112.75	70.25520838	0.25	17.56380209	205	0.085677083
80	0.623106061	111	69.16477277	0.25	17.29119319	205	0.084347284
70	0.623106061	114.25	71.18986747	0.25	17.79746687	205	0.086816912
60	0.623106061	124	77.26515156	0.25	19.31628789	205	0.094225795
50	0.623106061	134.75	83.96354172	0.25	20.99088543	205	0.102394563
40	0.623106061	153	95.33522733	0.25	23.83380683	205	0.116262472
30	0.623106061	160.5	100.0085228	0.25	25.0021307	205	0.121961613
20	0.623106061	160.25	99.85274628	0.25	24.96318657	205	0.121771642
10	0.623106061	117.25	73.05918565	0.25	18.26479641	205	0.089096568
0	0.623106061	0	0	0.25	0	205	0

Table 6-8 Knee MO2 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	152.75	95.17945082	0.25	23.7948627	205	0.116072501
110	0.623106061	129.75	80.84801141	0.25	20.21200285	205	0.098595136
100	0.623106061	114.5	71.34564398	0.25	17.836411	205	0.087006883
90	0.623106061	113.25	70.56676141	0.25	17.64169035	205	0.086057026
80	0.623106061	112.5	70.09943186	0.25	17.52485797	205	0.085487112
70	0.623106061	113.5	70.72253792	0.25	17.68063448	205	0.086246997
60	0.623106061	120.75	75.24005687	0.25	18.81001422	205	0.091756167
50	0.623106061	124	77.26515156	0.25	19.31628789	205	0.094225795
40	0.623106061	136	84.7424243	0.25	21.18560607	205	0.10334442
30	0.623106061	145.25	90.50615536	0.25	22.62653884	205	0.11037336
20	0.623106061	131.75	82.09422354	0.25	20.52355588	205	0.100114907
10	0.623106061	48	29.90909093	0.25	7.477272732	205	0.036474501
0	0.623106061	0	0	0.25	0	205	0

Table 6-9 Knee MO3 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	125.75	78.35558717	0.25	19.58889679	205	0.095555594
110	0.623106061	90	56.07954549	0.25	14.01988637	205	0.06838969
100	0.623106061	89.25	55.61221594	0.25	13.90305399	205	0.067819776
90	0.623106061	91.5	57.01420458	0.25	14.25355115	205	0.069529518
80	0.623106061	104.25	64.95880686	0.25	16.23970171	205	0.079218057
70	0.623106061	120.5	75.08428035	0.25	18.77107009	205	0.091566196
60	0.623106061	138.5	86.30018945	0.25	21.57504736	205	0.105244133
50	0.623106061	151.5	94.40056824	0.25	23.60014206	205	0.115122644
40	0.623106061	182.25	113.5610796	0.25	28.3902699	205	0.138489121
30	0.623106061	197.25	122.9076705	0.25	30.72691763	205	0.149887403
20	0.623106061	191.5	119.3248107	0.25	29.83120267	205	0.145518062
10	0.623106061	162.25	101.0989584	0.25	25.2747396	205	0.123291413
0	0.623106061	69.5	43.30587124	0.25	10.82646781	205	0.052812038

Table 6-10 Knee MO3 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	131.5	81.93844702	0.25	20.48461176	205	0.099924935
110	0.623106061	97	60.44128792	0.25	15.11032198	205	0.073708888
100	0.623106061	90.25	56.23532201	0.25	14.0588305	205	0.068579661
90	0.623106061	113	70.41098489	0.25	17.60274622	205	0.085867055
80	0.623106061	99.25	61.84327655	0.25	15.46081914	205	0.07541863
70	0.623106061	132.25	82.40577657	0.25	20.60144414	205	0.100494849
60	0.623106061	154.5	96.26988642	0.25	24.06747161	205	0.117402301
50	0.623106061	182	113.4053031	0.25	28.35132578	205	0.13829915
40	0.623106061	196.25	122.2845645	0.25	30.57114112	205	0.149127518
30	0.623106061	188.5	117.4554925	0.25	29.36387312	205	0.143238405
20	0.623106061	166	103.4356061	0.25	25.85890153	205	0.126140983
10	0.623106061	120.5	75.08428035	0.25	18.77107009	205	0.091566196

0	0.623106061	12	7.477272732	0.25	1.869318183	205	0.009118625

Table 6-11 Knee MO3 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	148	92.21969703	0.25	23.05492426	205	0.112463045
110	0.623106061	98.5	61.37594701	0.25	15.34398675	205	0.074848716
100	0.623106061	93	57.94886367	0.25	14.48721592	205	0.070669346
90	0.623106061	93.5	58.2604167	0.25	14.56510418	205	0.071049289
80	0.623106061	98	61.06439398	0.25	15.26609849	205	0.074468773
70	0.623106061	98.75	61.53172352	0.25	15.38293088	205	0.075038687
60	0.623106061	101.25	63.08948868	0.25	15.77237217	205	0.076938401
50	0.623106061	106.5	66.3607955	0.25	16.59019887	205	0.080927799
40	0.623106061	117.25	73.05918565	0.25	18.26479641	205	0.089096568
30	0.623106061	115.25	71.81297353	0.25	17.95324338	205	0.087576797
20	0.623106061	98.75	61.53172352	0.25	15.38293088	205	0.075038687
10	0.623106061	59.5	37.07481063	0.25	9.268702657	205	0.045213184
0	0.623106061	2	1.246212122	0.25	0.311553031	205	0.001519771

Table 6-12 Knee MO3 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	143.5	89.41571975	0.25	22.35392994	205	0.109043561
110	0.623106061	105	65.42613641	0.25	16.3565341	205	0.079787971
100	0.623106061	97	60.44128792	0.25	15.11032198	205	0.073708888
90	0.623106061	99	61.68750004	0.25	15.42187501	205	0.075228659
80	0.623106061	103	64.17992428	0.25	16.04498107	205	0.0782682
70	0.623106061	107.25	66.82812504	0.25	16.70703126	205	0.081497713
60	0.623106061	111.25	69.32054929	0.25	17.33013732	205	0.084537255
50	0.623106061	118.5	73.83806823	0.25	18.45951706	205	0.090046425

40	0.623106061	122.75	76.48626899	0.25	19.12156725	205	0.093275938
30	0.623106061	130.5	81.31534096	0.25	20.32883524	205	0.09916505
20	0.623106061	120.75	75.24005687	0.25	18.81001422	205	0.091756167
10	0.623106061	76.5	47.66761367	0.25	11.91690342	205	0.058131236
0	0.623106061	0	0	0.25	0	205	0

Table 6-13 Knee MO4 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	156	97.20454552	0.25	24.30113638	205	0.118542129
110	0.623106061	119	74.14962126	0.25	18.53740531	205	0.090426367
100	0.623106061	106	66.04924247	0.25	16.51231062	205	0.080547857
90	0.623106061	106.5	66.3607955	0.25	16.59019887	205	0.080927799
80	0.623106061	105	65.42613641	0.25	16.3565341	205	0.079787971
70	0.623106061	112.75	70.25520838	0.25	17.56380209	205	0.085677083
60	0.623106061	127	79.13446975	0.25	19.78361744	205	0.096505451
50	0.623106061	139	86.61174248	0.25	21.65293562	205	0.105624076
40	0.623106061	152.75	95.17945082	0.25	23.7948627	205	0.116072501
30	0.623106061	165.25	102.9682766	0.25	25.74206915	205	0.125571069
20	0.623106061	174	108.4204546	0.25	27.10511365	205	0.132220067
10	0.623106061	170.5	106.2395834	0.25	26.55989585	205	0.129560468
0	0.623106061	103	64.17992428	0.25	16.04498107	205	0.0782682

Table 6-14 Knee MO4 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	158.25	98.60653415	0.25	24.65163354	205	0.120251871
110	0.623106061	97.25	60.59706443	0.25	15.14926611	205	0.073898859
100	0.623106061	88.5	55.1448864	0.25	13.7862216	205	0.067249861
90	0.623106061	87	54.21022731	0.25	13.55255683	205	0.066110033

80	0.623106061	97.25	60.59706443	0.25	15.14926611	205	0.073898859
70	0.623106061	119.25	74.30539777	0.25	18.57634944	205	0.090616339
60	0.623106061	82.75	51.56202655	0.25	12.89050664	205	0.06288052
50	0.623106061	122	76.01893944	0.25	19.00473486	205	0.092706024
40	0.623106061	154.25	96.11410991	0.25	24.02852748	205	0.117212329
30	0.623106061	183.75	114.4957387	0.25	28.62393468	205	0.13962895
20	0.623106061	222.75	138.7968751	0.25	34.69921877	205	0.169264482
10	0.623106061	202.5	126.1789774	0.25	31.54474434	205	0.153876802
0	0.623106061	141.25	88.01373112	0.25	22.00343278	205	0.107333818

Table 6-15 Knee MO4 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	127.5	79.44602278	0.25	19.86150569	205	0.096885394
110	0.623106061	91	56.70265155	0.25	14.17566289	205	0.069149575
100	0.623106061	88.75	55.30066291	0.25	13.82516573	205	0.067439833
90	0.623106061	92.25	57.48153413	0.25	14.37038353	205	0.070099432
80	0.623106061	93.5	58.2604167	0.25	14.56510418	205	0.071049289
70	0.623106061	108.5	67.60700762	0.25	16.9017519	205	0.08244757
60	0.623106061	132	82.25000005	0.25	20.56250001	205	0.100304878
50	0.623106061	155	96.58143946	0.25	24.14535986	205	0.117782243
40	0.623106061	158	98.45075764	0.25	24.61268941	205	0.1200619
30	0.623106061	168.5	104.9933713	0.25	26.24834282	205	0.128040697
20	0.623106061	159.25	99.22964021	0.25	24.80741005	205	0.121011756
10	0.623106061	106	66.04924247	0.25	16.51231062	205	0.080547857
0	0.623106061	4.25	2.648200759	0.25	0.66205019	205	0.003229513

Table 6-16 Knee MO4 PS-TKA Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	130	81.00378793	0.25	20.25094698	205	0.098785107
110	0.623106061	92.5	57.63731064	0.25	14.40932766	205	0.070289403
100	0.623106061	86.25	53.74289776	0.25	13.43572444	205	0.065540119
90	0.623106061	92	57.32575761	0.25	14.3314394	205	0.069909461
80	0.623106061	103.75	64.64725383	0.25	16.16181346	205	0.078838114
70	0.623106061	114.25	71.18986747	0.25	17.79746687	205	0.086816912
60	0.623106061	128	79.75757581	0.25	19.93939395	205	0.097265336
50	0.623106061	140.25	87.39062506	0.25	21.84765626	205	0.106573933
40	0.623106061	158.75	98.91808718	0.25	24.7295218	205	0.120631814
30	0.623106061	179.25	111.6917614	0.25	27.92294036	205	0.136209465
20	0.623106061	181.5	113.0937501	0.25	28.27343752	205	0.137919207
10	0.623106061	148.75	92.68702657	0.25	23.17175664	205	0.113032959
0	0.623106061	1.5	0.934659092	0.25	0.233664773	205	0.001139828

Table 6-17 Knee MO5 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	198.75	123.8423296	0.25	30.96058241	205	0.151027231
110	0.623106061	111.75	69.63210232	0.25	17.40802558	205	0.084917198
100	0.623106061	102.75	64.02414777	0.25	16.00603694	205	0.078078229
90	0.623106061	104	64.80303034	0.25	16.20075759	205	0.079028086
80	0.623106061	106.25	66.20501898	0.25	16.55125475	205	0.080737828
70	0.623106061	116.75	72.74763262	0.25	18.18690816	205	0.088716625
60	0.623106061	128.5	80.06912884	0.25	20.01728221	205	0.097645279
50	0.623106061	141	87.8579546	0.25	21.96448865	205	0.107143847
40	0.623106061	156	97.20454552	0.25	24.30113638	205	0.118542129
30	0.623106061	169.5	105.6164773	0.25	26.40411933	205	0.128800582

20	0.623106061	174.75	108.8877842	0.25	27.22194604	205	0.132789981
10	0.623106061	155.75	97.048769	0.25	24.26219225	205	0.118352157
0	0.623106061	63.5	39.56723487	0.25	9.891808718	205	0.048252725

Table 6-18 Knee MO5 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	140.5	87.54640157	0.25	21.88660039	205	0.106763904
110	0.623106061	109.5	68.23011368	0.25	17.05752842	205	0.083207456
100	0.623106061	99.75	62.15482958	0.25	15.5387074	205	0.075798573
90	0.623106061	103.25	64.3357008	0.25	16.0839252	205	0.078458172
80	0.623106061	92.25	57.48153413	0.25	14.37038353	205	0.070099432
70	0.623106061	119.75	74.6169508	0.25	18.6542377	205	0.090996281
60	0.623106061	157.5	98.13920461	0.25	24.53480115	205	0.119681957
50	0.623106061	185	115.2746213	0.25	28.81865532	205	0.140578806
40	0.623106061	190.25	118.5459281	0.25	29.63648203	205	0.144568205
30	0.623106061	175.5	109.3551137	0.25	27.33877843	205	0.133359895
20	0.623106061	181.75	113.2495266	0.25	28.31238165	205	0.138109179
10	0.623106061	153	95.33522733	0.25	23.83380683	205	0.116262472
0	0.623106061	76	47.35606064	0.25	11.83901516	205	0.057751293

Table 6-19 Knee MO5 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	198.75	123.8423296	0.25	30.96058241	205	0.151027231
110	0.623106061	138	85.98863642	0.25	21.4971591	205	0.104864191
100	0.623106061	123.25	76.79782202	0.25	19.1994555	205	0.093655881
90	0.623106061	121.5	75.70738641	0.25	18.9268466	205	0.092326081
80	0.623106061	121.5	75.70738641	0.25	18.9268466	205	0.092326081

70	0.623106061	131.5	81.93844702	0.25	20.48461176	205	0.099924935
60	0.623106061	145.25	90.50615536	0.25	22.62653884	205	0.11037336
50	0.623106061	154.5	96.26988642	0.25	24.06747161	205	0.117402301
40	0.623106061	158	98.45075764	0.25	24.61268941	205	0.1200619
30	0.623106061	163.25	101.7220645	0.25	25.43051611	205	0.124051298
20	0.623106061	150.75	93.9332387	0.25	23.48330967	205	0.11455273
10	0.623106061	122.25	76.17471596	0.25	19.04367899	205	0.092895995
0	0.623106061	53.25	33.18039775	0.25	8.295099437	205	0.0404639

Table 6-20 Knee MO5 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	163.25	101.7220645	0.25	25.43051611	205	0.124051298
110	0.623106061	129.75	80.84801141	0.25	20.21200285	205	0.098595136
100	0.623106061	114.25	71.18986747	0.25	17.79746687	205	0.086816912
90	0.623106061	103.5	64.49147731	0.25	16.12286933	205	0.078648143
80	0.623106061	101.25	63.08948868	0.25	15.77237217	205	0.076938401
70	0.623106061	103.5	64.49147731	0.25	16.12286933	205	0.078648143
60	0.623106061	112.5	70.09943186	0.25	17.52485797	205	0.085487112
50	0.623106061	120.75	75.24005687	0.25	18.81001422	205	0.091756167
40	0.623106061	132.5	82.56155308	0.25	20.64038827	205	0.100684821
30	0.623106061	150.25	93.62168567	0.25	23.40542142	205	0.114172787
20	0.623106061	157.25	97.98342809	0.25	24.49585702	205	0.119491985
10	0.623106061	146	90.97348491	0.25	22.74337123	205	0.110943274
0	0.623106061	54.25	33.80350381	0.25	8.450875952	205	0.041223785

Table 6-21 Knee MO6 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	100.25	62.46638262	0.25	15.61659565	205	0.076178515
110	0.623106061	75.5	47.04450761	0.25	11.7611269	205	0.057371351
100	0.623106061	70.75	44.08475382	0.25	11.02118845	205	0.053761895
90	0.623106061	77.75	48.44649624	0.25	12.11162406	205	0.059081093
80	0.623106061	88.25	54.98910988	0.25	13.74727747	205	0.06705989
70	0.623106061	98	61.06439398	0.25	15.26609849	205	0.074468773
60	0.623106061	121.5	75.70738641	0.25	18.9268466	205	0.092326081
50	0.623106061	147.5	91.908144	0.25	22.977036	205	0.112083102
40	0.623106061	170	105.9280304	0.25	26.48200759	205	0.129180525
30	0.623106061	197.5	123.063447	0.25	30.76586176	205	0.150077374
20	0.623106061	211.25	131.6311554	0.25	32.90778885	205	0.160525799
10	0.623106061	206	128.3598486	0.25	32.08996214	205	0.156536401
0	0.623106061	96.5	60.12973489	0.25	15.03243372	205	0.073328945

Table 6-22 Knee MO6 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	130.25	81.15956445	0.25	20.28989111	205	0.098975079
110	0.623106061	74.5	46.42140154	0.25	11.60535039	205	0.056611465
100	0.623106061	75.25	46.88873109	0.25	11.72218277	205	0.057181379
90	0.623106061	77.5	48.29071973	0.25	12.07267993	205	0.058891122
80	0.623106061	92.75	57.79308716	0.25	14.44827179	205	0.070479375
70	0.623106061	73.75	45.954072	0.25	11.488518	205	0.056041551
60	0.623106061	130.5	81.31534096	0.25	20.32883524	205	0.09916505
50	0.623106061	169	105.3049243	0.25	26.32623108	205	0.128420639
40	0.623106061	201.5	125.5558713	0.25	31.38896782	205	0.153116916
30	0.623106061	216.5	134.9024622	0.25	33.72561555	205	0.164515198

20	0.623106061	198.5	123.6865531	0.25	30.92163828	205	0.15083726
10	0.623106061	161	100.3200758	0.25	25.08001896	205	0.122341556
0	0.623106061	45.5	28.35132578	0.25	7.087831444	205	0.034574788

Table 6-23 Knee MO6 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	126.5	78.82291672	0.25	19.70572918	205	0.096125508
110	0.623106061	81	50.47159094	0.25	12.61789774	205	0.061550721
100	0.623106061	74.25	46.26562503	0.25	11.56640626	205	0.056421494
90	0.623106061	74.75	46.57717806	0.25	11.64429451	205	0.056801437
80	0.623106061	83.25	51.87357958	0.25	12.96839489	205	0.063260463
70	0.623106061	97.75	60.90861746	0.25	15.22715437	205	0.074278802
60	0.623106061	108.25	67.4512311	0.25	16.86280778	205	0.082257599
50	0.623106061	113.25	70.56676141	0.25	17.64169035	205	0.086057026
40	0.623106061	127.5	79.44602278	0.25	19.86150569	205	0.096885394
30	0.623106061	136	84.7424243	0.25	21.18560607	205	0.10334442
20	0.623106061	123.25	76.79782202	0.25	19.1994555	205	0.093655881
10	0.623106061	70	43.61742427	0.25	10.90435607	205	0.053191981
0	0.623106061	1	0.623106061	0.25	0.155776515	205	0.000759885

Table 6-24 Knee MO6 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	109	67.91856065	0.25	16.97964016	205	0.082827513
110	0.623106061	84.25	52.49668564	0.25	13.12417141	205	0.064020348
100	0.623106061	82.75	51.56202655	0.25	12.89050664	205	0.06288052

90	0.623106061	88.25	54.98910988	0.25	13.74727747	205	0.06705989
80	0.623106061	94.5	58.88352276	0.25	14.72088069	205	0.071809174
70	0.623106061	100.75	62.77793565	0.25	15.69448391	205	0.076558458
60	0.623106061	115.25	71.81297353	0.25	17.95324338	205	0.087576797
50	0.623106061	125.25	78.04403414	0.25	19.51100854	205	0.095175651
40	0.623106061	139.5	86.92329551	0.25	21.73082388	205	0.106004019
30	0.623106061	154.5	96.26988642	0.25	24.06747161	205	0.117402301
20	0.623106061	151.75	94.55634476	0.25	23.63908619	205	0.115312616
10	0.623106061	104.25	64.95880686	0.25	16.23970171	205	0.079218057
0	0.623106061	1.5	0.934659092	0.25	0.233664773	205	0.001139828

Table 6-25 Knee MO9 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	158.5	98.76231067	0.25	24.69057767	205	0.120441842
110	0.623106061	98.25	61.22017049	0.25	15.30504262	205	0.074658745
100	0.623106061	85.5	53.27556822	0.25	13.31889205	205	0.064970205
90	0.623106061	91	56.70265155	0.25	14.17566289	205	0.069149575
80	0.623106061	99.5	61.99905307	0.25	15.49976327	205	0.075608601
70	0.623106061	119	74.14962126	0.25	18.53740531	205	0.090426367
60	0.623106061	132.75	82.7173296	0.25	20.6793324	205	0.100874792
50	0.623106061	159.25	99.22964021	0.25	24.80741005	205	0.121011756
40	0.623106061	168.5	104.9933713	0.25	26.24834282	205	0.128040697
30	0.623106061	184	114.6515152	0.25	28.66287881	205	0.139818921
20	0.623106061	187.75	116.988163	0.25	29.24704074	205	0.142668491
10	0.623106061	163.5	101.877841	0.25	25.46946024	205	0.124241269
0	0.623106061	79.25	49.38115533	0.25	12.34528883	205	0.060220921

Table 6-26 Knee MO9 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	117	72.90340914	0.25	18.22585228	205	0.088906597
110	0.623106061	78.25	48.75804927	0.25	12.18951232	205	0.059461036
100	0.623106061	78.25	48.75804927	0.25	12.18951232	205	0.059461036
90	0.623106061	65.75	40.96922351	0.25	10.24230588	205	0.049962468
80	0.623106061	65	40.50189397	0.25	10.12547349	205	0.049392554
70	0.623106061	74.5	46.42140154	0.25	11.60535039	205	0.056611465
60	0.623106061	62.5	38.94412881	0.25	9.736032203	205	0.04749284
50	0.623106061	101.25	63.08948868	0.25	15.77237217	205	0.076938401
40	0.623106061	141.75	88.32528415	0.25	22.08132104	205	0.107713761
30	0.623106061	178.5	111.2244319	0.25	27.80610797	205	0.135639551
20	0.623106061	200.25	124.7769887	0.25	31.19424718	205	0.152167059
10	0.623106061	189.5	118.0785986	0.25	29.51964964	205	0.143998291
0	0.623106061	142.75	88.94839021	0.25	22.23709755	205	0.108473647

Table 6-27 Knee MO9 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	120	74.77272732	0.25	18.69318183	205	0.091186253
110	0.623106061	81.75	50.93892049	0.25	12.73473012	205	0.062120635
100	0.623106061	71	44.24053033	0.25	11.06013258	205	0.053951866
90	0.623106061	74.75	46.57717806	0.25	11.64429451	205	0.056801437
80	0.623106061	78.75	49.0696023	0.25	12.26740058	205	0.059840978
70	0.623106061	86	53.58712125	0.25	13.39678031	205	0.065350148
60	0.623106061	92	57.32575761	0.25	14.3314394	205	0.069909461
50	0.623106061	107.5	66.98390156	0.25	16.74597539	205	0.081687685
40	0.623106061	112.75	70.25520838	0.25	17.56380209	205	0.085677083
30	0.623106061	130	81.00378793	0.25	20.25094698	205	0.098785107

20	0.623106061	146	90.97348491	0.25	22.74337123	205	0.110943274
10	0.623106061	114.75	71.5014205	0.25	17.87535512	205	0.087196854
0	0.623106061	25.25	15.73342804	0.25	3.93335701	205	0.019187107

Table 6-28 Knee MO9 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	114.75	71.5014205	0.25	17.87535512	205	0.087196854
110	0.623106061	84.5	52.65246215	0.25	13.16311554	205	0.06421032
100	0.623106061	73	45.48674245	0.25	11.37168561	205	0.055471637
90	0.623106061	73.25	45.64251897	0.25	11.41062974	205	0.055661608
80	0.623106061	71.75	44.70785988	0.25	11.17696497	205	0.05452178
70	0.623106061	80.5	50.16003791	0.25	12.54000948	205	0.061170778
60	0.623106061	85	52.96401519	0.25	13.2410038	205	0.064590262
50	0.623106061	92.5	57.63731064	0.25	14.40932766	205	0.070289403
40	0.623106061	106	66.04924247	0.25	16.51231062	205	0.080547857
30	0.623106061	129	80.38068187	0.25	20.09517047	205	0.098025222
20	0.623106061	145.5	90.66193188	0.25	22.66548297	205	0.110563332
10	0.623106061	121.25	75.5516099	0.25	18.88790247	205	0.09213611
0	0.623106061	14.5	9.035037885	0.25	2.258759471	205	0.011018339

Table 6-29 Knee MO10 Native Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	165.75	103.2798296	0.25	25.8199574	205	0.125951012
110	0.623106061	124.75	77.73248111	0.25	19.43312028	205	0.094795709
100	0.623106061	110	68.54166671	0.25	17.13541668	205	0.083587398
90	0.623106061	104.25	64.95880686	0.25	16.23970171	205	0.079218057
80	0.623106061	103.25	64.3357008	0.25	16.0839252	205	0.078458172

70	0.623106061	103.75	64.64725383	0.25	16.16181346	205	0.078838114
60	0.623106061	126.25	78.6671402	0.25	19.66678505	205	0.095935537
50	0.623106061	147	91.59659097	0.25	22.89914774	205	0.11170316
40	0.623106061	147	91.59659097	0.25	22.89914774	205	0.11170316
30	0.623106061	163	101.5662879	0.25	25.39157199	205	0.123861327
20	0.623106061	191.5	119.3248107	0.25	29.83120267	205	0.145518062
10	0.623106061	168.25	104.8375948	0.25	26.20939869	205	0.127850725
0	0.623106061	28	17.44696971	0.25	4.361742427	205	0.021276792

Table 6-30 Knee MO10 PFA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	149.5	93.15435612	0.25	23.28858903	205	0.113602873
110	0.623106061	116.5	72.59185611	0.25	18.14796403	205	0.088526654
100	0.623106061	116.75	72.74763262	0.25	18.18690816	205	0.088716625
90	0.623106061	109.25	68.07433716	0.25	17.01858429	205	0.083017484
80	0.623106061	100.75	62.77793565	0.25	15.69448391	205	0.076558458
70	0.623106061	104.75	65.27035989	0.25	16.31758997	205	0.079598
60	0.623106061	135	84.11931824	0.25	21.02982956	205	0.102584534
50	0.623106061	170.5	106.2395834	0.25	26.55989585	205	0.129560468
40	0.623106061	194.5	121.1941289	0.25	30.29853222	205	0.147797718
30	0.623106061	205	127.7367425	0.25	31.93418563	205	0.155776515
20	0.623106061	203.75	126.9578599	0.25	31.73946498	205	0.154826658
10	0.623106061	162.75	101.4105114	0.25	25.35262786	205	0.123671355
0	0.623106061	19	11.83901516	0.25	2.95975379	205	0.014437823

Table 6-31 Knee MO10 CR-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	177.75	110.7571023	0.25	27.68927559	205	0.135069637

110	0.623106061	139.25	86.76751899	0.25	21.69187975	205	0.105814048
100	0.623106061	118.25	73.68229171	0.25	18.42057293	205	0.089856453
90	0.623106061	119	74.14962126	0.25	18.53740531	205	0.090426367
80	0.623106061	120.75	75.24005687	0.25	18.81001422	205	0.091756167
70	0.623106061	137.5	85.67708339	0.25	21.41927085	205	0.104484248
60	0.623106061	155	96.58143946	0.25	24.14535986	205	0.117782243
50	0.623106061	160	99.69696976	0.25	24.92424244	205	0.12158167
40	0.623106061	159.75	99.54119324	0.25	24.88529831	205	0.121391699
30	0.623106061	164.25	102.3451705	0.25	25.58629263	205	0.124811184
20	0.623106061	165.25	102.9682766	0.25	25.74206915	205	0.125571069
10	0.623106061	141.25	88.01373112	0.25	22.00343278	205	0.107333818
0	0.623106061	56.75	35.36126896	0.25	8.84031724	205	0.043123499

Table 6-32 Knee MO10 PS-TKA Mean Data

Flexion Angle (°)	Force Multiplication Factor	Corrected Mean	Force (N)	Distance (m)	Moment (Nm)	Constant Force (N)	Extensor Moment Efficiency (Nm/N_{QT})
120	0.623106061	169.5	105.6164773	0.25	26.40411933	205	0.128800582
110	0.623106061	129.5	80.6922349	0.25	20.17305872	205	0.098405165
100	0.623106061	134.5	83.8077652	0.25	20.9519413	205	0.102204592
90	0.623106061	130.75	81.47111748	0.25	20.36777937	205	0.099355021
80	0.623106061	104.75	65.27035989	0.25	16.31758997	205	0.079598
70	0.623106061	112.5	70.09943186	0.25	17.52485797	205	0.085487112
60	0.623106061	140.25	87.39062506	0.25	21.84765626	205	0.106573933
50	0.623106061	157.25	97.98342809	0.25	24.49585702	205	0.119491985
40	0.623106061	175.5	109.3551137	0.25	27.33877843	205	0.133359895
30	0.623106061	163.5	101.877841	0.25	25.46946024	205	0.124241269
20	0.623106061	153.5	95.64678036	0.25	23.91169509	205	0.116642415
10	0.623106061	107	66.67234853	0.25	16.66808713	205	0.081307742
0	0.623106061	29.5	18.3816288	0.25	4.5954072	205	0.02241662

Appendix II: Extensor Mechanism Efficiency Summary Data for Conditions

Table 6-33 Native Knee Data

Flexion Angle (°)	Extensor Moment Efficiency (Nm/N_{QT})								Mean	Standard Deviation (±SD)
	MO1	MO2	MO3	MO4	MO5	MO6	MO9	MO10		
120	0.104294277	0.095745565	0.095555594	0.118542129	0.151027231	0.076178515	0.120441842	0.125951012	0.110967021	0.022992127
110	0.0782682	0.078648143	0.06838969	0.090426367	0.084917198	0.057371351	0.074658745	0.094795709	0.078434425	0.012026183
100	0.075608601	0.078458172	0.067819776	0.080547857	0.078078229	0.053761895	0.064970205	0.083587398	0.072854017	0.009947681
90	0.079598	0.077128372	0.069529518	0.080927799	0.079028086	0.059081093	0.069149575	0.079218057	0.074207563	0.007628606
80	0.084347284	0.083397427	0.079218057	0.079787971	0.080737828	0.06705989	0.075608601	0.078458172	0.078576904	0.005405666
70	0.088906597	0.090426367	0.091566196	0.085677083	0.088716625	0.074468773	0.090426367	0.078838114	0.086128265	0.006213244
60	0.098975079	0.102394563	0.105244133	0.096505451	0.097645279	0.092326081	0.100874792	0.095935537	0.098737614	0.004061441
50	0.109803446	0.11170316	0.115122644	0.105624076	0.107143847	0.112083102	0.121011756	0.11170316	0.111774399	0.004777897
40	0.123101441	0.117022358	0.138489121	0.116072501	0.118542129	0.129180525	0.128040697	0.11170316	0.122768991	0.008736765
30	0.127660754	0.119681957	0.149887403	0.125571069	0.128800582	0.150077374	0.139818921	0.123861327	0.133169923	0.011864142
20	0.125001155	0.123671355	0.145518062	0.132220067	0.132789981	0.160525799	0.142668491	0.145518062	0.138489121	0.012393356
10	0.115502587	0.102394563	0.123291413	0.129560468	0.118352157	0.156536401	0.124241269	0.127850725	0.124716198	0.01545371
0	0.029825504	0.026406019	0.052812038	0.0782682	0.048252725	0.073328945	0.060220921	0.021276792	0.048798893	0.021500585

Table 6-34 PFA Knee Data

Flexion Angle (°)	Extensor Moment Efficiency (Nm/N_{QT})								Mean	Standard Deviation (±SD)
	MO1	MO2	MO3	MO4	MO5	MO6	MO9	MO10		
120	0.131460181	0.113602873	0.099924935	0.120251871	0.106763904	0.098975079	0.088906597	0.113602873	0.109186039	0.013441732
110	0.082257599	0.070289403	0.073708888	0.073898859	0.083207456	0.056611465	0.059461036	0.088526654	0.07349517	0.011272952
100	0.058131236	0.064400291	0.068579661	0.067249861	0.075798573	0.057181379	0.059461036	0.088716625	0.067439833	0.010614623
90	0.052052153	0.059271064	0.085867055	0.066110033	0.078458172	0.058891122	0.049962468	0.083017484	0.066703694	0.014056574
80	0.073708888	0.038564186	0.07541863	0.073898859	0.070099432	0.070479375	0.049392554	0.076558458	0.066015048	0.014078403
70	0.089856453	0.06288052	0.100494849	0.090616339	0.090996281	0.056041551	0.056611465	0.079598	0.078386932	0.017502108
60	0.105434105	0.092516052	0.117402301	0.06288052	0.119681957	0.09916505	0.04749284	0.102584534	0.09339467	0.025548134
50	0.128610611	0.123101441	0.13829915	0.092706024	0.140578806	0.128420639	0.076938401	0.129560468	0.119776943	0.022688203
40	0.134309752	0.146087976	0.149127518	0.117212329	0.144568205	0.153116916	0.107713761	0.147797718	0.137491772	0.016552211
30	0.130890267	0.153116916	0.143238405	0.13962895	0.133359895	0.164515198	0.135639551	0.155776515	0.144520712	0.012042596
20	0.115692558	0.150647289	0.126140983	0.169264482	0.138109179	0.15083726	0.152167059	0.154826658	0.144710684	0.017171667
10	0.090426367	0.135639551	0.091566196	0.153876802	0.116262472	0.122341556	0.143998291	0.123671355	0.122222824	0.022818024
0	0.011778224	0.088526654	0.009118625	0.107333818	0.057751293	0.034574788	0.108473647	0.014437823	0.053999359	0.042690844

Table 6-35 CR-TKA Knee Data

Flexion Angle (°)	Extensor Moment Efficiency (Nm/N_{QT})								Mean	Standard Deviation (±SD)
	MO1	MO2	MO3	MO4	MO5	MO6	MO9	MO10		
120	0.116642415	0.093845852	0.112463045	0.096885394	0.151027231	0.096125508	0.091186253	0.135069637	0.111655667	0.02177609
110	0.073898859	0.089666482	0.074848716	0.069149575	0.104864191	0.061550721	0.062120635	0.105814048	0.080239153	0.017804957
100	0.070099432	0.087196854	0.070669346	0.067439833	0.093655881	0.056421494	0.053951866	0.089856453	0.073661395	0.015077398
90	0.075798573	0.085677083	0.071049289	0.070099432	0.092326081	0.056801437	0.056801437	0.090426367	0.074872462	0.013911315
80	0.069149575	0.084347284	0.074468773	0.071049289	0.092326081	0.063260463	0.059840978	0.091756167	0.075774826	0.012428433
70	0.073328945	0.086816912	0.075038687	0.08244757	0.099924935	0.074278802	0.065350148	0.104484248	0.082708781	0.013662829
60	0.085297141	0.094225795	0.076938401	0.100304878	0.11037336	0.082257599	0.069909461	0.117782243	0.09213611	0.016607949
50	0.086436969	0.102394563	0.080927799	0.117782243	0.117402301	0.086057026	0.081687685	0.12158167	0.099283782	0.017582048
40	0.1187321	0.116262472	0.089096568	0.1200619	0.1200619	0.096885394	0.085677083	0.121391699	0.108521139	0.015263294
30	0.101634678	0.121961613	0.087576797	0.128040697	0.124051298	0.10334442	0.098785107	0.124811184	0.111275724	0.015190159
20	0.102584534	0.121771642	0.075038687	0.121011756	0.11455273	0.093655881	0.110943274	0.125571069	0.108141197	0.017074112
10	0.078648143	0.089096568	0.045213184	0.080547857	0.092895995	0.053191981	0.087196854	0.107333818	0.07926555	0.020614112

0	0.022796563	0	0.001519771	0.003229513	0.0404639	0.000759885	0.019187107	0.043123499	0.01638503	0.017929843

Table 6-36 PS-TKA Knee Data

Flexion Angle (°)	Extensor Moment Efficiency (Nm/N_{QT})								Mean	Standard Deviation (±SD)
	MO1	MO2	MO3	MO4	MO5	MO6	MO9	MO10		
120	0.115122644	0.116072501	0.109043561	0.098785107	0.124051298	0.082827513	0.087196854	0.128800582	0.107737508	0.016725014
110	0.088146711	0.098595136	0.079787971	0.070289403	0.098595136	0.064020348	0.06421032	0.098405165	0.082756274	0.015282598
100	0.080167914	0.087006883	0.073708888	0.065540119	0.086816912	0.06288052	0.055471637	0.102204592	0.076724683	0.015335303
90	0.07541863	0.086057026	0.075228659	0.069909461	0.078648143	0.06705989	0.055661608	0.099355021	0.075917305	0.013011874
80	0.06838969	0.085487112	0.0782682	0.078838114	0.076938401	0.071809174	0.05452178	0.079598	0.074231309	0.009477784
70	0.07123926	0.086246997	0.081497713	0.086816912	0.078648143	0.076558458	0.061170778	0.085487112	0.078458172	0.008813876
60	0.076558458	0.091756167	0.084537255	0.097265336	0.085487112	0.087576797	0.064590262	0.106573933	0.086793165	0.01270941
50	0.077888258	0.094225795	0.090046425	0.106573933	0.091756167	0.095175651	0.070289403	0.119491985	0.093180952	0.0153365
40	0.080927799	0.10334442	0.093275938	0.120631814	0.100684821	0.106004019	0.080547857	0.133359895	0.10234707	0.01824255
30	0.094795709	0.11037336	0.09916505	0.136209465	0.114172787	0.117402301	0.098025222	0.124241269	0.111798145	0.014283811
20	0.105624076	0.100114907	0.091756167	0.137919207	0.119491985	0.115312616	0.110563332	0.116642415	0.112178088	0.013907816
10	0.067249861	0.036474501	0.058131236	0.113032959	0.110943274	0.079218057	0.09213611	0.081307742	0.079811718	0.026003472
0	0.023366477	-0.000379943	0	0.001139828	0.041223785	0.001139828	0.011018339	0.02241662	0.012490617	0.015231171

Appendix III: Patellofemoral Resultant Force Summary Data for Conditions

Table 6-37 Patellofemoral Resultant Force Summary Data

Native knee		
Flexion angle (°)	Mean Patellofemoral Resultant Force (N)	Standard deviation (±SD)
0	36.27738597	4.443786551
30	68.64461041	9.654367135
60	91.10694451	21.27002882
90	92.12674547	30.56885352
120	83.38981248	28.14018458
PFA		
Flexion angle (°)	Mean Patellofemoral Resultant Force (N)	Standard deviation (±SD)
0	30.08964813	9.988692998
30	54.66419394	12.67898517
60	71.39603169	16.47218708
90	101.9181354	29.26405569
120	97.27299288	30.78750053
CR-TKA		
Flexion angle (°)	Mean Patellofemoral Resultant Force (N)	Standard deviation (±SD)
0	22.868891	4.034754054
30	51.09061188	8.23142143
60	82.2397565	13.6216609
90	82.9544755	15.21988778
120	83.20235925	24.47742336
PS-TKA		
Flexion angle (°)	Mean Patellofemoral Resultant Force (N)	Standard deviation (±SD)
0	25.47978425	4.573377099
30	51.06743731	5.853063028
60	81.64295675	12.63350876
90	76.239756	14.6552731
120	73.35268	12.9374087

Appendix IV: Peak Pressure Summary Data for Conditions

Table 6-38 Peak Pressure Summary Data

Native knee		
Flexion angle (°)	Mean Peak Pressure (MPa)	Standard deviation (±SD)
0	1.651428571	0.563232592
30	1.194285714	0.629758079
60	1.186428571	0.569632296
90	1.431428571	0.639900476
120	1.730714286	1.761796972
PFA		
Flexion angle (°)	Mean Peak Pressure (MPa)	Standard deviation (±SD)
0	7.130625	1.326064094
30	7.835625	0.540300429
60	8.2525	0.758890167
90	4.436875	1.550340832
120	3.056875	0.927711999
CR-TKA		
Flexion angle (°)	Mean Peak Pressure (MPa)	Standard deviation (±SD)
0	6.6925	0.88663489
30	7.25875	0.998426441
60	7.56875	1.154270796
90	8.026875	1.198057766
120	8.10125	1.172386912
PS-TKA		
Flexion angle (°)	Mean Peak Pressure (MPa)	Standard deviation (±SD)
0	6.906875	1.238775137
30	7.00625	0.708397336
60	7.520625	0.921863166
90	8.058125	1.017777472
120	8.246875	0.602506298

Appendix V: Contact Area Summary Data for Conditions

Table 6-39 Contact Area Summary Data

Native knee		
Flexion angle (°)	Mean Contact Area (mm^2)	Standard deviation (±SD)
0	117.3960786	25.11180992
30	229.0318	31.99483024
60	338.1329643	69.95493072
90	308.4095214	56.85874213
120	288.0178571	59.20395571
PFA		
Flexion angle (°)	Mean Contact Area (mm^2)	Standard deviation (±SD)
0	19.65721875	9.960671924
30	38.60879375	17.5016771
60	44.2538875	9.983952568
90	106.1489813	37.36853831
120	108.1651069	20.4037425
CR-TKA		
Flexion angle (°)	Mean Contact Area (mm^2)	Standard deviation (±SD)
0	13.9112375	4.910196488
30	30.76606875	11.69634516
60	47.78210625	6.122803842
90	36.29025	14.12685751
120	32.258	8.865711765
PS-TKA		
Flexion angle (°)	Mean Contact Area (mm^2)	Standard deviation (±SD)
0	13.306425	6.050294814
30	17.9435125	7.886852467
60	44.85878125	15.62538683
90	32.05633125	6.660500529
120	28.12491875	5.442999346

Appendix VI: Additional Systematic Review Tables

Table 6-40 Details of Implant Characteristics

Year of inception	Implant	Implant Design characteristics			Studies
		Onlay/ Inlay	**Asymmetric/ Symmetric**	**Anatomical/ Non-anatomical**	
1974/76/84	Richards I, II, III	Inlay	Symmetric	Non-anatomical	Blazina et al 1979 Arciero et al 1988* Kradjca-Radcliffe et al 1996 Arnbjornsson et al 1998* Kooijman et al 2003 Cartier et al 2005 Utukuri et al 2008 van Jonbergen et al 2010
1975	Lubinus	Inlay	Asymmetric	Non-anatomical	Arnbjornsson et al 1998* Tauro et al 2001 Smith et al 2002 Board et al 2004 Mohammed et al 2008*
1976	CSF-Wright	Inlay	Symmetric	Non-anatomical	Arciero et al 1988*
1980	Autocentric I, II	Inlay	Asymmetric	Non-anatomical	Argenson et al 2005 van Wagenberg et al 2009
1987	Spherocentric	Inlay	Asymmetric	Non-anatomical	
1997	LCS	Inlay	Asymmetric	Anatomical	Merchant 2005 Charalambous et al 2011
1996	Avon	Onlay	Symmetric	Non-anatomical	Nicol et al 2006 Ackroyd et al 2007 Hollinghurst et al 2007 Mohammed et al 2008* Leadbetter et al 2009

					Odumenya et al 2010 Gao et al 2011 Sarda et al 2011 Mont et al 2012
1997	Hermes	Onlay	Asymmetric	Anatomical	Goutailler et al 2008
2004?	Vanguard	Onlay	Asymmetric	Anatomical	
2008	Natural Knee II	Onlay	Asymmetric	Anatomical	Hofmann et al 2009
1996	FPV	Onlay	Asymmetric	Anatomical	Mohammed et al 2008* Monk et al 2012 Mofidi et al 2012
2005	Journey	Onlay	Asymmetric	Anatomical	Beitzel et al 2012
2008?	Zimmer	Onlay	Asymmetric	Anatomical	
1994?	Custom Performa Knee	Onlay	Asymmetric	Anatomical-patient specific	Butler et al 2009
1995	Kinematch	Onlay	Asymmetric	Anatomical-patient specific	Sisto & Sarin 2010

*Mixed group

Table 6-41 Surgery performed prior to, during and after PFA or TKA

Author	Implant	List of procedures		
Inlay, symmetrical, non-anatomical		Pre-operative	Concomitant procedures	Post-operative
Blazina 1979 cemented – *nr* surgeons – *nr*	Richards I and II	25 patellaplasties 2 secondary patellaplasties 24 medial meniscetomies 4 secondary medial menisectomies 8 lateral menisectomies Proximal extensor realignment procedures: 23 vastus medialis transposition 3 secondary medialis transportion 7 medial patellar retinaculum advancement 2 secondary medial patellar retinaculum advancement 23 vastus lateralis release 2 vastus lateralis release Distal extensor realignment procedures: 12 Tibial tubercle transfer 4 Roux-Goldthwaite 2 transfer medial ½ of patellar tendon Other: 3 patella # ORIF 6 Removal of loose bodies 5 chondroplasty of lateral femoral condyle 4 partial excision of fat pad 3 chondroplasty of femoral groove 2 Ellison 2 partial synovectomy 2 chondroplasty of medial femoral condyle 2 Excision of neuroma of infrapatellar branch of saphenous nerve 2 anteromedial capsular reefing 2 posteromedial capsular reefing	-	13 lateral capsule release 9 release of intra-articular adhesions 9 tibial tubercle transfer 7 partial excision of fat pad 6 V-plasty lengthening of patellar tendon 6 medial capsule release 5 secondary(revision) femoral groove replacement 4 vastus lateralis release 3 secondary vastus lateralis release 3 partial synovectomy 3 PFR 2 Z-plasty lengthening Of patellar tendon 2 lateral facetectomy of patella 2 debridement and irrigation of wound 2 secondary vastus medialis transposition 2 removal of PFR 1 secondary patellar replacement 21 miscellaneous

		2 pes anserinus transfer 21 miscellaneous		
	TOTAL	**195 (in 66pts)**		**101 (in 30pts)**
Krajca-Radcliffe 1996 cemented – all surgeons - 1	Richards I and II	1 menisectomy 1 arthroscopy and lateral release 1 arthrotomy with loose body removal 1 patella # ORIF	13 lateral releases	2 partial meniscetomies 1 PFR 1 Hauser procedure
	TOTAL	**4 (in 4pts)**	**13**	**4 (in 3pts)**
de Winter 2001 cemented – all surgeons - *nr*	Richards II	7 soft tissue patellar realignment 3 TT transfer 7 arthroscopies 1 arthrotomy 3 meniscetomies 1 patella # ORIF	-	3 patellectomies 3 nettoyages (arthroscopic washout) 2 TKR 2 realignment procedures (one soft tissue patellar realignment and 1 TT transfer) 2 MUAs
	TOTAL	**22 (in 12pts)**		**12 (in 11pts)**
Kooijman 2003 cemented – all surgeons - *nr*	Richards II	7 Maquet procedures 5 realignment procedures 2 patella # ORIF 42 patella debridements	-	8 procedures: MUA, arthroscopic or open debridement of joint 7 revision PFRs: 1 patellar loosening 1 maltracking 2 malpositioning 3 patellectomies 2 femoral component removed 3 HTOs 10 TKAs
	TOTAL	**74 (in 38pts)**		**30 (in 19pts)**
Cartier 2005 cemented – all surgeons - *nr*	Richards II	10 TT transfers 3 soft tissue surgery 1 PFR 3 menisectomies 1 HTO	15 TT transfers 2 HTOs 1 medial retinaculum tightening	1 realignment of trochlear prosthesis 1 reduce thickness of old TT advancement 3 lateral releases 8 TKRs
	TOTAL	**18 (in 18 knees)**	**18 (in 18 knees)**	**13 (in 13 knees)**
Utukuri 2008 cemented – all surgeons - 1	Richards II	20 arthroscopic evaluations 3 Lateral releases	-	-
	TOTAL	**23 (in 17pts)**		
van Jonbergen 2010 cemented – all surgeons – 3	Richards II	25 realignment procedures 109 patelloplasties 24 menisectomies 19 Other	5 distal realignment 1 debridement chondral lesion medial fem cond 1 metal removal from previous	11 MUAs 14 arthrotomies 27 arthroscopies 10 Other Removal of prosthesis due to:

			realignment	1 infection 2 malposition 23 TKR for TFOA PFR: 10 malposition 4 loosening 4 wear
	TOTAL	**177 (in 157pts)**	**7 (in 7pts)**	**105 (in 77pts)**
Inlay, asymmetrical, non-anatomical				
Tauro 2001 cemented – all surgeons – *nr*		-	2 medial UKR (St George Sled) 37 lateral releases	15 revisions for patellar maltracking: 5 TKR 10 PFR (Avons) 5 TKR for TFOA 1 TKR for # patella and SC femur # 3 Roux – Goldthwaite 7 patellar buttons inserted as secondary procedure 4 arthroscopies 1 patella # ORIF
	TOTAL		**39**	**36**
Smith 2002 cemented – *nr* surgeons – 5		11 arthroscopies	-	3 TKR for TFOA 1 TKR for pain 1 TKR for patellar instability 2 PFR for patellar maltracking 1 TT transfer 2 medial plications
	TOTAL	**11**		**10**
Board 2004 cemented – all surgeons – *nr*		5 arthroscopy washouts 1 lateral release 1 tibial tubercle 1 Roux-Goldthwaite 1 patella # ORIF	7 lateral releases	TKR: 2 for TFOA 1 for infection 1 for 10° extension block 1 PFR for 15° ext block 2 arthroscopies
	TOTAL	**9**	**7**	**7**
Argenson 2005 cemented – all surgeons – multiple		12 patella # ORIF 6 TT transfer (anterior TT elevation)	8 osteotomies: - 3 HTO - 5 lower femoral osteotomies 5 TT transfer (anterior TT for medialisation)	TKR: 14 for TFOA 4 for loosening 4 for stiffness PFR for loosening: 3 infection 3 aseptic loosening 1 patella # 2 MUA 5 lateral releases + partial patellectomy (lateral patellar facet resection)
	TOTAL	**18**	**12**	**36**

Van Wagenberg 2009 cemented – 3; others uncemented surgeons – *nr*		20 arthroscopies	2 lateral releases	7 TKR 7 arthroscopic nettoyage (washout) 1 arthrotomic debridement 1 excision of neuroma 2 hydrops decompression punctuation 13 intra-articular injection 2 lateral release 1 resurfacing patella edge 4 revision patellar component 1 surgical intervention wound infection
	TOTAL	**20**	**2**	**39**
Inlay, asymmetrical, anatomical				
Merchant 2005 cemented – all femoral; some press-fit patella surgeons – 6		Multiple lateral retinacular releases Realignment procedures	Multiple lateral retinacular releases Realignment procedures	-
	TOTAL	***nr***	***nr***	
Charalambous 2011 cemented – all surgeons – 2		-	-	12 TKR for pain (2 coexisting TFOA): - 6 reduced mobility due to tissue overgrowth - 3 extensive metalosis - 2 PE worn and fractured - 1 maltracking 4 TKR for patellar instability or dissociation of patellar bearing 1 revision patellar component 1 Lateral retinacular release for patella maltracking
	TOTAL			**18**

Onlay, symmetrical, non-anatomical				
Nicol 2006 cemented – all surgeons – 2		13 arthroscopy 2 chondrectomy 2 patellar realignment 1 patella # ORIF 1 UKR 9 unknown	-	12 TKR for TFOA 1 TKR for lateral femoral condyle necrosis 1 TKR persistent pain and patellar subluxation
	TOTAL	**28**		**14**
Ackroyd 2007 cemented – all surgeons – multiple		15 arthroscopies 3 chondrectomy 2 lateral releases 2 patellar realignment 1 patella # ORIF	-	2 arthroscopic haemarthrosis evacuations 1 MUA 1 distal soft tissue realignment 4 TKR for TFOA (later 11 TKR for TFOA not included in analysis)
	TOTAL	**23**		**8**
Hollinghurst 2007 cemented – all surgeons – *nr*		-	-	-
	TOTAL			
Leadbetter 2009 cemented – all surgeons – multiple		48 arthroscopic PF shaving or chondroplasty 10 lateral releases 9 anteromedialisation TT osteotomies 8 osteoarticular graftings 3 soft tissue realignments 2 ACL reconstructions 1 HTO	-	4 TKR for TFOA 1 TKR for instability 1 TKR for trauma 1 TT # ORIF following a fall
	TOTAL	**81**		**7**
Starks 2009 cemented – all surgeons – 1		6 arthroscopies 1 lateral release 1 patella # ORIF 1 autologous chondrocyte implantation	-	1 patellar resurfacing as a secondary procedure 1 revision patellar component
	TOTAL	**9**		**2**
Odumenya 2010 cemented – all surgeons – 1		22 arthroscopies 5 lateral releases 2 chondrectomies 1 patella # ORIF	-	1 arthroscopic lateral release 2 TKR for persistent pain/mild TFOA 1 TKR for TFOA
	TOTAL	**30**		**4**
Gao 2010 cemented – all		11 arthroscopies 6 lateral releases	1 arthroscopic menisectomy	-

surgeons – 1				
	TOTAL	**17**	**1**	
Sarda 2011 cemented – all surgeons – 1		6 lateral releases 6 chondrectomy	6 lateral releases	1 TKR for TFOA 1 TKR for clicking 6 lateral releases 2 arthroscopic excisions of nodular lesions
	TOTAL	**12**	**6**	**10**
Mont 2012 cemented – all surgeons – 3		-	-	1 open arthrotomy 4 arthroscopic lysis of adhesions 5 TKR 1 MUA
	TOTAL			**11**
Onlay, asymmetrical, anatomical				
Hofmann 2009 cemented – all surgeons – 4		-	-	Following trauma in 2 cases: 1 medial retinacular repair 1 lateral release 1 medialisation of patellar component 1 revision femoral component
	TOTAL			**4**
Monk 2012 cemented – all surgeons – 1		-	-	-
	TOTAL			
Mofidi 2012 cemented – all surgeons – 2		-	-	-
	TOTAL			
Williams 2013 cemented – all surgeons – 6		2 patellar ORIF 2 patellar realignment		5 TKR: 4 for TFOA 1 for inflammatory arthritis 1 PFR for persistent pain 1 TKR for persistent pain 1 patellar ORIF
	TOTAL	**4**		**8**
Beitzel 2013 cemented – all surgeons – 4		8 retro-patellar debridement/shaving 1 microfracture 1 OATS 1 TT transfer	4 MPFL reconstructions 2 medial tightening 2 distal femur osteotomies	none

	TOTAL	**11**	**8**	
Onlay, asymmetrical, patient-specific				
Butler 2009 cemented – none surgeons – *nr*		Multiple arthroscopy procedures	-	1 revision patellar component 2 arthroscopic debridement for arthrofibrosis
	TOTAL	***nr***		**3**
Sisto 2010 cemented – all surgeons – 1		13 arthroscopic lateral release and debridement 6 arthrotomy with lateral release and elevation of the tibial tubercle	12 lateral release	none
	TOTAL	**19**	**12**	
Mixed group				
Arciero 1988 cemented – all surgeons – 9		Realignment procedures: 2 Hausers 1 Maquet 2 lateral releases 4 arthroscopy meniscal procedures 1 arthroscopic removal of loose body	7 lateral releases 2 TT transfers 2 UKRs 1 VMO ADV	3 UKR 2 arthroscopies 2 revision PFA 3 MUAs 1 open lysis of adhesions
	TOTAL	**10**	**12**	**11**
Arnbjornsson 1998 cemented – *nr* surgeons – multiple		30 arthroscopy +/- menisectomy 2 tibial osteotomy 18 lateral release 2 TT transfer 6 other alignment procedure 11 TT elevation 6 other ops	none	6 rev PFA (change or patellar comp) for pain 3 TKR for pain 1 arthrodesis for pain 5 patellectomy for pain 11 arthroscopy/-tomy 8 lateral release 10 MUA 4 medial TT transfer 4 tibial osteotomy 3 synovectomy for infection 3 extr. osteosyntesm. 3 other operations
	TOTAL	**75**		**61**
Mohammed 2008 cemented – all surgeons – multiple		58 arthroscopy + debridement 15 chondroplasty 23 lateral retinalcular release 3 TT transfer 18 intra-articular injections	23 lateral releases 6 osteochondral autograft transfer system (OATS) procedure	2 MUA 18 arthroscopic debridement 8 arthroscopic lateral release 3 tibial tubercle transfer 4 TKR
	TOTAL	**117**	**29**	**35**

Total knee replacement				
Meding 2007 cemented – all AGC – CR-TKR Legacy – PS-TKR surgeons – 5		unknown	10 lateral release	none
	TOTAL	***nr***	**1**	
Laskin 1999 cemented – all Genesis – CR-TKR surgeons – 1		-	18 lateral release	-
	TOTAL		**18**	
Thompson 2001 cemented – none LCS – PS-TKR without patellar resurfacing surgeons – 1		7 injections 1 operation for patellar dislocation	Unknown number of lateral release	-
	TOTAL	**8**	***nr***	
Mont 2002 cemented – cemented/uncemented/hybrids (metal-back/all- poly patellar components) 24 – PS-TKR 6 – CR-TKR surgeons – multiple		none	12 lateral releases	1 patellar tendon reconstruction
	TOTAL		**12**	**1**
Dalury 2005 cemented – all Press Fit Condylar CR-TKR surgeons – 1		-	3 lateral release	-
	TOTAL		**3**	
Parvizi 2001 cemented – all PS-TKR CR-TKR surgeons – multiple		2 arthroscopic menisectomy 1 proximal extensor realignment 1 open lateral release 1 supracondylar femur # ORIF	21 lateral release	1 MUA 1 revision of patellar component 1 proximal extensor mechanism alignment 1 tibial poly exchange
	TOTAL	**5**	**21**	**4**

Comparison				
Dahm 2010 cemented – all Avon PFR surgeons – >1		13 procedures	19 lateral release	none
	TOTAL	**13**	**19**	
Dahm 2010 cemented – all PS-TKR CR-TKR surgeons – 8		9 procedures	1 lateral release	1 MUA
	TOTAL	**9**	**1**	**1**

Table 6-42 Mechanism of failure for all knees requiring revision to TKA or other PFA, UKA, arthrodesis or removal

Author Year	Implant	Knees	Disease Progression (TFOA)	Number of Malposition/ misalignment	Number of persistent pain	Aseptic loosening	Infection	Other (stiffness, trauma etc)
Inlay, symmetrical, non-anatomical								
Blazina 1979	Richards I and II	85	0	9	1	0	1	0
Krajca-Radcliffe 1996	Richards I and II	16	0	1	0	0	0	0
de Winter 2001	Richards II	26	2	0	0	0	0	0
Kooijman 2003	Richards II	45	10	3	*not reported*	1	0	5
Cartier 2005	Richards II	59	8	5	0	0	0	0
Utukuri 2008	Richards II	20	0	0	0	0	0	0
van Jonbergen 2010	Richards II	181	23	12	0	4	1	5
Inlay, asymmetrical, non-anatomical								
Tauro 2001	Lubinus	76	5	15	7	0	0	1
Smith 2002	Lubinus	29	3	3	1	0	0	0
Board 2004	Lubinus	17	2	2	0	0	1	0
Argenson 2005	Autocentric	57	14	0	0	7	3	5
Van Wagenberg 2009	Autocentric II	24	7	4	0	0	0	0
Inlay, asymmetrical, anatomical								
Merchant 2005	LCS	16	0	0	0	0	0	0

Charalambous 2011	LCS	51	2*	3	12*	0	0	3
Onlay, symmetrical, non-anatomical								
Nicol 2006	Avon	103	12	1*	1*	0	0	1
Ackroyd 2007	Avon	109	4	0	0	0	0	0
Hollinghurst 2007	Avon	12	0	0	0	0	0	0
Leadbetter 2009	Avon	79	4	1	0	0	0	1
Starks 2009	Avon	37	0	0	1	0	0	1
Odumenya 2010	Avon	50	3*	0	2*	0	0	0
Gao 2010	Avon	11	0	0	0	0	0	0
Sarda 2011	Avon	44	1	1*	1*	0	0	0
Mont 2012	Avon	43	2*	0	0	5*	0	0
Onlay, asymmetrical, anatomical								
Hofmann 2009	Natural Knee II	40	0	0	0	0	0	2
Monk 2012	FPV	15	0	0	0	0	0	0
Mofidi 2012	FPV	34	0	0	0	0	0	0
Williams 2013	FPV	53	4	0	2	0	0	1
Beitzel 2013	Journey	22	0	0	0	0	0	0
Onlay, asymmetrical, patient-specific								
Butler	Custom Performa	22	0	0	0	0	0	1

2009	Knee							
Sisto 2010	Kinematch	25	0	0	0	0	0	0
Mixed Group								
Arciero 1988	Richards and CSF-Wright	25	3	2	0	0	0	0
Arnbjornsson 1998	Richards I and II Lubinus Miscellaneous other	113	0	0	10	0	0	0
Mohammed 2008	Lubinus Avon FPV	101	3	0	0	0	1	0
Total Knee Replacement								
Meding 2007	AGC Legacy	33	0	0	0	0	0	0
Laskin 1999	Genesis	48	0	0	0	0	0	0
Thompson 2001	LCS	33	0	0	0	0	0	0
Mont 2002	Porous Coated Anatomic Duracon Insall-Burstein II	30	0	0	0	0	0	0
Dalury 2005	Press Fit Condylar	33	0	0	0	0	0	0
Parvizi 2001	Press Fit Condylar Genesis Total Condylar	31	0	1	0	1	0	0
Comparison								
Dahm 2010	Avon	23	0	0	0	0	0	0
Dahm 2010	Zimmer SIGMA	22	0	0	0	0	0	0

* knees with dual pathology

Table 6-43 Details of clinical outcomes

Author Year	Implant	Knees/Subjects (available for follow-up)	Clinical Score	Pre- operative Score	Post-operative Score
Inlay, symmetrical, non-anatomical					
Blazina 1979	Richards I and II	**57/55**	*nr*	*nr*	*nr*
Krajca-Radcliffe 1996	Richards I and II	**16/13**	Modified Hungerford and Kenna Scale Satisfaction	*nr*	88% (90-100) 14 (88%) satisfactory = excellent or good. 12 excellent 2 good 1 fair 1 poor
de Winter 2001	Richards II	**21/21**	AKSS: Function/Clinical Satisfaction	*nr*	80(0-100)/95(65-100) 9 excellent 7 good 4 improved 1 unimproved
Kooijman 2003	Richards II	**35/35**	AKSS: Function/Clinical Satisfaction	*nr*	167 30 good to excellent 5 fair to poor
Cartier 2005	Richards II	**59/50**	AKSS: Function/Clinical	*nr*	Function: 72% excellent 19% fair 9% failure Clinical: 77% excellent 14% fair 9% failure
Utukuri 2008	Richards II	**20/17**	HSS SF-36 • Physical functioning • Social functioning • Role limitations due to physical problems • Role limitations due to emotional problems • Pain • General health perceptions • Mental health • Energy/vitality KOOS • Pain • Other symptoms • Function in daily living • Function in sports &	64(51-79) *nr* *nr*	90(71-100) 14 excellent (85-100) 3 good (70-84) 58 73 72 68 60 61 72 63 70 68

			recreation • Knee related quality of life		73 57 51
van Jonbergen 2010	Richards II	**181/157**	*nr*	*nr*	*nr*
Inlay, asymmetrical, non-anatomical					
Tauro 2001	Lubinus	**62/48**	Bristol Knee Score > or 90 = excellent 80-89 = good 70-79 = fair < 70 = poor <80 or revised = unsatisfactory Bristol pain score Bristol movement score	55(29-86) pain: 5(0-20) = continual severe 100(90-120)	72 (42-100) Satisfactory 28/62 (45%) Unsatisfactory 34/62 (55%) Pain: 30(15-40) = occasional mild 112(70-120)
Smith 2002	Lubinus	**29/21**	Modified Hungerford and Kenna score 90 or > = excellent 80-89 = good 70-79 = fair <70 = poor Crosby and Insall grading system Excellent/good/fair/worse	 *nr* *nr*	 13 excellent 10 good 2 fair 4 poor 2 excellent 21 good 4 fair/poor 2 worse
Board 2004	Lubinus	**17/12**	Tegner score Lysholm score VAS (pain) Satisfaction	*nr* *nr* 5(5-9)	2(1-3) 46(16-84) 7(1-9) 10 knees (59%) satisfactory 7 knees (41%) disappointed
Argenson 2005	Autocentric	**29/29**	AKSS: Function/Clinical	41(10-80)/53(43-70)	81(40-100)/79(60-100)
Van Wagenberg 2009	Autocentric II	**10/10**	OKS KOOS • Pain • Other symptoms • Function in daily living • Function in sports & recreation • Knee related quality of life SF-36 • Physical functioning • Social functioning • Role limitations due to	*nr* *nr* *nr*	36(±11) 48(±22) 60(±20) 43(±18) 22(±13) 42(±20) 32(±20) 58(±22) 20(±37)

			physical problems • Role limitations due to emotional problems • Pain • General health perceptions • Mental health • Energy/vitality VAS (pain)	 *nr*	47(±50) 50(±27) 53(±21) 64(±17) 50(±16) 4(±3)
Inlay, asymmetrical, anatomical					
Merchant 2005	LCS	**16/16**	Activities of Daily Living Scale 85-100% = excellent 70-84% = good 55-69% = fair	 *nr* *nr* 42%(23-73) *8pts	8 [84%(74-96)*8pts] 7
Charalambous 2011	LCS	**28/-**	OKS AKSS: Function/Clinical Melbourne Patellar Score Satisfaction: Compared with before surgery Much better Better Same Worse	*nr* *nr* *nr*	35(26-44) 80(63-100)/87(63-88) 25(16-30) 10 12 3 3
Onlay, symmetrical, non-anatomical					
Nicol 2006	Avon	**66/-**	*nr*	*nr*	*nr*
Ackroyd 2007	Avon	**109/85**	OKS Bristol Pain Score Melbourne Patellar Score	18(13-24) 15(5-20) 10(6-15)	39(24-45) 35(20-40) 25(20-29)
Hollinghurst 2007	Avon	**12/12**	AKSS: Function/Clinical OKS Bartlett (Melbourne) Patellar Score	*nr* *nr* *nr*	85(45-100)/88(73-100) 37(19-47) 26(18-30)
Leadbetter 2009	Avon	**79/70**	AKSS: Function/Clinical	56	83 (34 knees > 90; 32 knees > 80)
Starks 2009	Avon	**37/29**	AKSS: Function/Clinical	*nr*	85(60-100)/95(90-100) 32knees ≥ 80

			OKS Melbourne Patellar Score Satisfaction	*nr* *nr*	in clinical score = excellent in 86% 39(32-44) 28(21-30) 28 pts satisfied
Odumenya 2010	Avon	**50/32**	OKS EuroQol	*nr* *nr*	31(22-42) bilaterals: 50(25-85) unilaterals: 75(25-100)
Gao 2010	Avon	**11/11**	WOMAC Score AKSS: Function/Clinical	38(±8) 54(±11)/70(±11)	21(±5) 95(±4)/96(±4)
Sarda 2011	Avon	**44/40**	Melbourne Patellar Score AKSS: Function/Clinical Satisfaction	10(5-21) 57(23-95) mean	25(11-30) 85(28-100) mean 34 good or excellent 3 fair 2 poor/worse
Mont 2012	Avon	**43/37**	AKSS: Function/Clinical	48(45-50)/64(57-68)	82(20-100)/87(50-100)
Onlay, asymmetrical, anatomical					
Hofmann 2009	Natural Knee II	**40/34**	KOOS • Pain • Other symptoms • Function in daily living • Function in sports & recreation • Knee related quality of life Tegner Score Satisfaction	*nr* 3	 93 94 94 70 82 5 40 satisfactory
Monk 2012	FPV	**15/8**	OKS AKSS: Function / Clinical	33(±8) 53(±14)/62(±6)	42(±3) 86(±12)/88(±7)
Mofidi 2012	FPV	**34/28**	OKS AKSS: Function/Clinical	30(±6) 42(±12)/49(±12)	21(±12) 67(±16)/80(±20)
Williams 2013	FPV	**53/48**	*nr*	*nr*	*Nr§*
Beitzel 2013	Journey	**22/22**	WOMAC Lysholm Score VAS (pain)	*nr* *nr* *nr*	All scores improved significantly (no values given; just

					graphs)
Onlay, asymmetrical, patient-specific					
Butler 2009	Custom Performa Knee	**22/21**	WOMAC	63	28
Sisto 2010	Kinematch	**25/22**	Satisfaction		25 very satisfied
Mixed Group					
Arciero 1988	Richards and CSF-Wright	**25/22**	Modified Hungerford and Kenna Score 90 or > = excellent 80-89 = good 70-79 = fair <70 = poor	*nr*	 9 9 0 7
Arnbjornsson 1998	Richards I and II Lubinus Miscellaneous other	**113/97**	Lysholm Score Satisfaction	45(20-64)	62(6-100) 85/113 satisfied
Mohammed 2008	Lubinus Avon FPV	**101/91**	*nr*	*nr*	*nr*
Total Knee Arthroplasty					
Meding 2007	AGC Legacy	**33/27**	AKSS: Functional/Clinical	55(35-80)/49(20-64)	83(45-100)/88(33-99)
Laskin 1999	Genesis	**48/48**	AKSS: Functional/Clinical (pain only)	71(62-80)/25(20-30)	96(82-100)/47(30-50)
Thompson 2001	LCS	**33/31**	-	-	-
Mont 2002	Porous Coated Anatomic Duracon Insall-Burstein II	**30/27**	AKSS: Functional/Clinical	49(20-80)/50(20-64)	86(60-100)/93(67-100)
Dalury 2005	Press Fit Condylar	**33/25**	AKSS: Functional/Clinical (pain only)	62(36-80)/22(16-30)	96(92-100)/46(40-50)
Parvizi 2001	Press Fit Condylar Genesis Total Condylar	**31/24**	AKSS: Functional/Clinical	36(0-80)/54(32-90)	90(20-100)/89(54-100)
Comparison					
Dahm 2010	Avon	**-/23**	AKSS: Functional/Clinical UCLA score	42/58 3	84(51-100)/89(69-100)

			Tegner score	2	7(5-9) 4(3-6)
Dahm 2010	Zimmer SIGMA	**-/22**	AKSS: Functional/Clinical UCLA score Tegner score	43/59 3 2	73(59-94)/90(47-100) 4(3-6) 3(2-3)

VAS, Visual Analogue Scale; HSS, Hospital for Special Surgery score; SF-36, Short Form 36; KOOS, Knee Injury and Osteoarthritis Outcome Score; AKSS, American Knee Society Score; OKS, Oxford Knee Score (0-worst, 48-best score; 12-best, 60-worst score); EuroQol- EuroQol VAS General Health Score; UCLA- University of California Los Angeles activity score

Table 6-44 Heterogeneity Assessment for Survival Proportions A and B

Design Category	I_2 Calculation %	
	Survival Proportion A	Survival Proportion B
Inlay symmetrical non-anatomical	79.9%	79.2%
Inlay asymmetrical non-anatomical	57.5%	44.8%
Inlay asymmetrical anatomical	*%	*%
Onlay symmetrical non-anatomical	30.2%	14.3%
Onlay asymmetrical anatomical	0%	0%
Onlay asymmetrical patient-specific	*%	*%
Mixed	74.7%	68.3%
Total Knee Arthroplasty	0%	0%

The Avon has an arc of curvature of approximately 90°, similar to the normal geometry of the distal femur, and an anterior flange that is straight in the sagittal plane, unlike the Lubinus (IAN group), Richards (ISN group) or Autocentric (IAN group). This allows the trochlear prosthesis to lie flat on the surface of the anterior femur, and flush within the intercondylar notch. The sulcus angle of the Avon is broader (approximately 125°) than the small Lubinus (approximately 110°) and is therefore less constraining in extension and more accommodating to slight patellar tilt or subluxation. The wider sulcus angle allows the patellar component greater freedom of medial-lateral translation when it enters the trochlear groove, unlike the narrower Lubinus, which offered less freedom of movement and could therefore be subjected to higher shear forces.

The trochlear component is symmetrical so one component is used for both left and right. The justification for this design was that the prosthesis aligned with the mechanical axis, not the anatomical one, and therefore sided prostheses were not necessary (Wright *et al.*, 1990). This concept was supported by Iranpour *et al*. (2010a), who found that the patella moved in a circular path about the axis of the trochlea and this path was aligned with the mechanical axis of the femur (see Figure 6-1). The patellar component is anatomical, mimicking the seven facets of the natural patella. It has a central crest offset towards the medial side. The medial and lateral sides each have a superior, central and inferior facet. The medial

edge is thicker than the lateral, due to the offset crest and is smoothed to create an articular surface similar to the odd facet. In the original design the medial edge scored the medial condyle, hence the change.

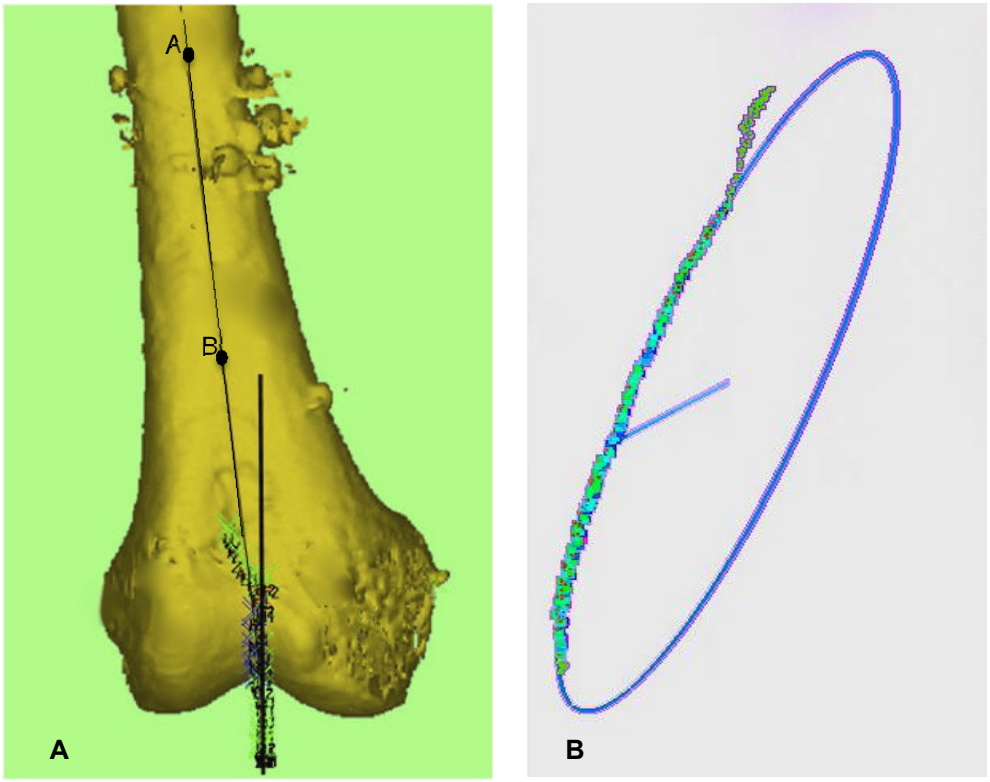

Figure 6-1 [A] The bold black line highlights the circular path of the patella and its relationship to the anatomical axis (AB) illustrating it is more fitted to the mechanical axis. [B] Further demonstrates the circular nature of the path of the patella, illustrating the lateral deviation of the path near extension.

Appendix VII: Trial Documents

Trial Documents 1: Patient Information Sheet

Participant information sheet

The Patellofemoral Arthroplasty Trial

Chief Investigator: Mr Matt Costa

Background information
Over 50,000 patients with severe arthritis of the knee undergo Knee Arthroplasty (Replacement) each year in the UK. The majority of these patients have arthritis that affects all of the surfaces of the knee joint. Therefore they have a 'Total' Knee Arthroplasty, where the whole knee joint is replaced. However, approximately 10% of patients have arthritis that only affects the patellofemoral surfaces of the joint i.e. the area around the knee-cap.

Traditionally patients with arthritis affecting only the patellofemoral part of the knee have still had a Total Knee Arthroplasty. However, it is also possible to replace only the patellofemoral part of the knee joint. This is called a Patellofemoral Arthroplasty.

Both Total Knee Arthroplasty and Patellofemoral Arthroplasty are routinely available to NHS patients with severe arthritis of the patellofemoral part of the knee. The difference between the two involves the number of joint surfaces replaced. In Total Knee Arthroplasty all three major areas of the joint are replaced with metal and plastic surfaces. In Patellofemoral Arthroplasty only the back of the knee-cap and the groove that the knee cap sits in are replaced with metal and plastic surfaces.

What is the purpose of this study?
This study aims to determine the best type of arthroplasty for patients with severe arthritis of the patellofemoral part of the knee. We are comparing two treatments – Total Knee Arthroplasty and Patellofemoral Arthroplasty.

Why have I been chosen?
You have been chosen because you have severe arthritis of the patellofemoral part of the knee joint and your surgeon thinks that you may benefit from an arthroplasty operation.

Do I have to take part?
It is up to you whether or not to take part. If you decide to take part you will be given this information sheet to keep and be asked to sign a consent form. If you decide to take part you are still free to withdraw at any time and without giving a reason. A decision to withdraw at any time or a decision not to take part will not affect the standard of care you receive.

Which treatment will I get?
If you agree to take part, you will be randomly allocated to either the Total Knee Arthroplasty or the Patellofemoral Arthroplasty. The allocation process will be done by a computer and will be done purely by chance. In order that we can make a

fair comparison between the two types of operation, you will not be told which type of arthroplasty you have had for the duration of the study.

What will happen after I have been placed in one of the two groups?
Once you have agreed to take part, you will be asked to fill out some questionnaires and a doctor or physiotherapist will do some tests on your knee - such as test your range of movement. The questionnaires we will ask you to fill out contain questions about your activity level and how well you are able to perform certain day-to-day tasks and also about how you feel.

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University Hospitals Coventry and Warwickshire NHS Trust

You will then be sent a date to have your surgery in the usual way. Whether you are allocated a Total Knee Arthroplasty or a Patellofemoral Arthroplasty, the operation will take place in the usual manner by your surgeon.

After the operation, we will keep a careful check on your progress for a year. In this period you will be given the same questionnaires as you filled out before the operation on three occasions (3, 6 and 12 months after the operation).

What are the possible disadvantages and risks of taking part?
We do not know which of these treatments gives the best results. Since both types of arthroplasty involve surgery, there are risks for both groups. However, these risks are the same as for patients not taking part in the trial. There are no special risks over and above what your surgeon would normally inform you about.

What are the possible benefits of taking part?
Both Total Knee Arthroplasty and Patellofemoral Arthroplasty are already being used in the NHS for people with severe arthritis of the patellofemoral part of the knee joint. There is therefore no specific advantage to you for taking part in the study. However, the information we get from this study may help us to choose the best type of arthroplasty for patients with the same sort of arthritis as you.

What if new information becomes available?
Sometimes during the course of a research project, new information becomes available about the treatment that is being studied. If this happens, we will tell you about it and discuss with you whether you want to continue in the study. If you decide to withdraw your care will continue as normal for the hospital. If you decide to continue in the study you will be asked sign an updated consent form. On receiving new information we may consider it to be in your best interest to withdraw you from the study. We will explain the reasons and arrange for your care to continue.

What happens when the research study ends?
You will be in the study for 12 months. However, at the end of the study, we will continue to send you questionnaires each year and your surgeon will send you appointments for x-rays from time to time in the usual way for patients who have had a knee arthroplasty.

What happens if something goes wrong?
In the unlikely event of you being harmed by taking part in this research project, there are no special compensation arrangements. If you are harmed due to someone's negligence, then you may have grounds for a legal action but you may have to pay for it. Regardless of this, if you wish to complain, or have any concerns about any aspect of the way you have been approached or treated during the course of this study, please contact Mr Peter Hedges at Research & Support Services, University House, University of Warwick, Kirby Corner Road, Coventry CV4 8UW. Direct telephone number 024 765 23716.

Will my taking part in this study be kept confidential?
All information which is collected about you during the course of the research will be kept strictly confidential. Any information about you which leaves the hospital will have your name and address removed so that you cannot be recognised from it. Your GP and other doctors who may treat you, but are not part of this study will be notified that you are taking part in this study.

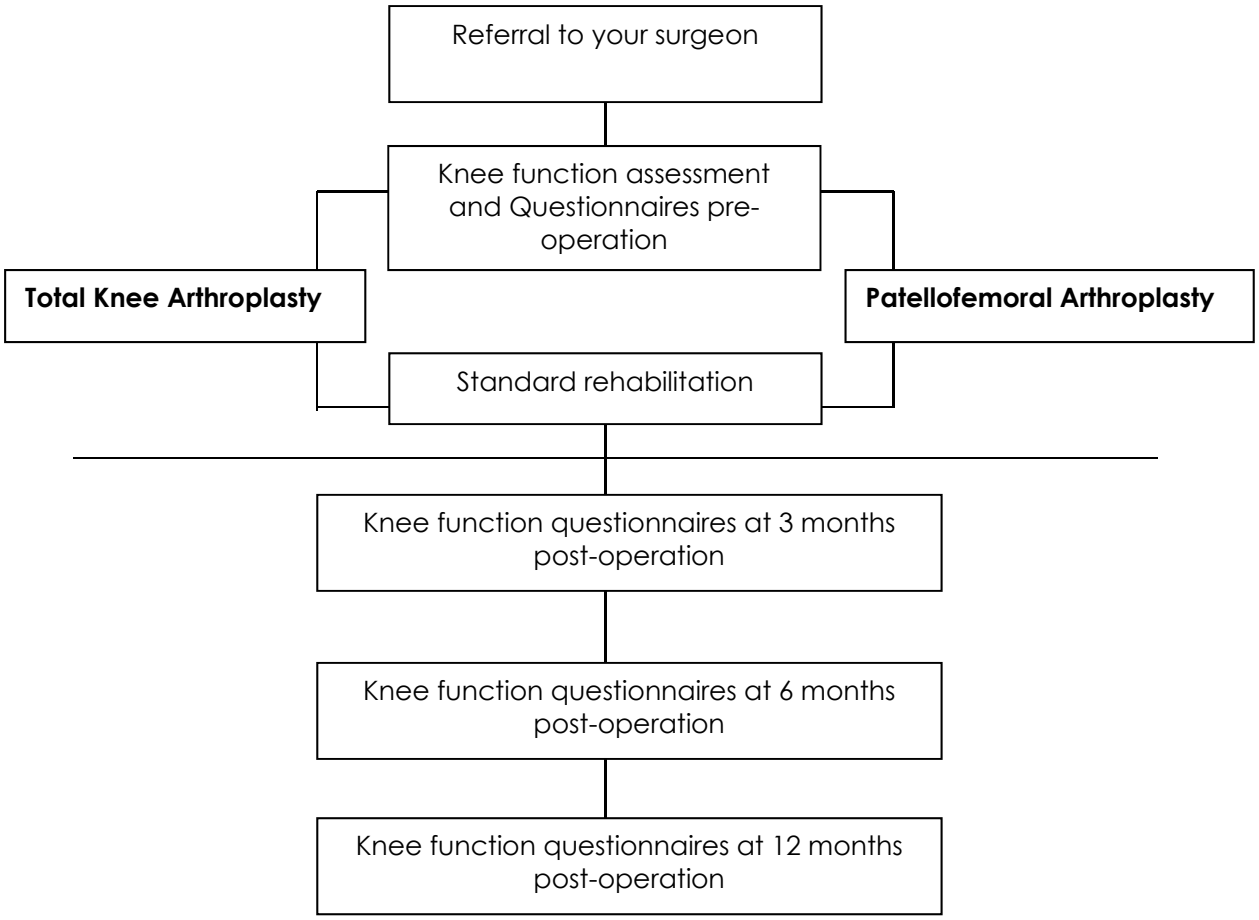
What will happen to the results of the research study?
This study is expected to last 3 years. At the end of the study we will publish the findings in medical journals and at medical conferences. You will not be identified in any reports or publications resulting from the study. If you would like to obtain a copy of the published results, please ask your doctor.

What will happen if I decide not to participate in the research study?
If you decide not to participate in the research study you may choose to have a Total Knee Arthroplasty or a Patellofemoral Arthroplasty, after being informed by your doctor.

Who has reviewed this study?
This study has been reviewed by the Coventry Local Research Committee

Contacts for further information
If you would like further information please contact Mr Matt Costa, who is leading the project by telephoning 02476 968618 or Dr Juul Achten who is responsible for the day-to-day management of the study (02476 968614, J.Achten@warwick.ac.uk).

Flow chart of the study



THE UNIVERSITY OF WARWICK

University Hospitals Coventry and Warwickshire NHS Trust

PUBLICATIONS

Joseph, M.N., Carmont, M.R., Tailor, H., Stephen, J., Lumpaopong, P. and Amis, A.A. Extensor Mechanism Efficiency following Patellofemoral Arthroplasty and Total Knee Arthroplasty: A Cadaveric Biomechanical Study. *Bone & Joint Journal Proceedings* 2015

Odumenya, M., Krikler, S.J. and Amis, A.A. The Ideal Patellofemoral Arthroplasty. La Patella - 15èmes Journèes Lyonnaises de Chirurgie du Genou ALRM. Sauramps Medical 2012 [Book chapter]

Odumenya, M., McGuinness, K., Achten, J., Parsons, N., Spalding, T. and Costa, M. (2011) The Warwick Patellofemoral Arthroplasty Trial: A Randomised Clinical Trial of Total Knee Arthroplasty versus Patellofemoral Arthroplasty in Patients with Severe Arthritis of the Patellofemoral Joint. *BMC Musculoskeletal Disorders*, **12**, 265

Odumenya, M., Costa, M.L., Parsons, N., Achten, J., Dhillon, M. and Krikler, S.J. (2010) The Avon Patellofemoral Joint Replacement: Five-year Results from an Independent Centre. *Journal of Bone and Joint Surgery- British Volume*, **92B**(1), pp. 56-60

PRESENTATIONS

Extensor Mechanism Efficiency Following Patellofemoral Arthroplasty and Total Knee Arthroplasty: A Cadaveric Biomechanical Study.

British Association for Surgery of the Knee (BASK). Telford, March 2015

British Orthopaedic Association (BOA). Birmingham, October 2013

Bone Research Society and British Orthopaedic Research Society (BRS BORS). Oxford, September 2013

The Warwick Patellofemoral Arthroplasty Trial: A Randomised Clinical Trial of Total Knee Arthroplasty versus Patellofemoral Arthroplasty in Patients with Severe Arthritis of the Patellofemoral Joint.

European Patellofemoral Meeting. Copenhagen, September 2014

Systematic Review of the Survival Proportion and Complications following the Use of Patellofemoral Arthroplasty and Total Knee Arthroplasty for the Treatment of Severe Isolated Patellofemoral Arthritis.

Bone Research Society and British Orthopaedic Research Society (BRS BORS). Oxford, September 2013

European Federation of National Associations of Orthopaedics and Traumatology (EFORT). Istanbul, June 2013

International Society of Arthroscopy, Knee Surgery and Orthopaedic Sports Medicine (ISAKOS). Toronto, May 2013

The Principles of an Ideal Patellofemoral Arthroplasty

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