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Compartmental Arthroplasty in the Treatment of Osteoarthritis of the Knee

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Declaration of Originality

I declare that all material in this thesis is my own, except where specifically identified and referenced. No part of this thesis has previously been submitted for the award of a degree by this or any other University. This work was conducted between October 2017 and December 2021 under the supervision of Professor Justin Cobb, Dr Richard van Arkel and Professor Andrew Amis. The section on biomechanics included close collaboration with Mr Oliver Dandridge, PhD Candidate, Imperial College. During the relevant sections it is made explicitly clear which work was my own and which was the work of others. The work was kindly funded by the Sir Michael Uren Foundation, The Dunhill Medical Trust, The Royal College of Surgeons of England and the Sackler Trust. Infrastructure support was provided by the National Institute for Health Research (NIHR) Imperial Biomedical Research Centre (BRC). Surgical instruments and implants for the in vitro study were supplied by Zimmer Biomet® (Warsaw, USA).

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Abstract

INTRODUCTION: Compartmental Arthroplasty: ipsilateral combinations of partial knee arthroplasty (CPKA), are Anterior Cruciate Ligament (ACL) preserving alternatives to Total Knee Arthroplasty (TKA) in the treatment of osteoarthritis. This thesis investigates the biomechanics, gait characteristics and patient reported outcomes of CPKA.

METHODS: In vitro, the extensor moment, relative implant efficiency and anterior-posterior stability, of cadaveric specimens were determined with varying implant combinations in situ. CPKA subjects were measured on an instrumented treadmill at top walking speeds, then compared to matched healthy and primary posterior-cruciate retaining TKA subjects using the vertical component of ground reaction forces and temporospatial measurements. Finally, satisfaction was determined using the Oxford Knee Score and quality of life was assessed using the EuroQol-5D.

RESULTS: In vitro, UKA and CPKA generated the same extensor moment as native knees at low flexion angles, where TKA were less efficient. In deep flexion, the extensor mechanism was marginally more efficient following TKA than CPKA. Overall efficiency of UKA and CPKA were near-normal but significantly reduced following TKA. UKA and BCA demonstrated normal anterior-posterior stability, whilst Bi-UKA demonstrated increased anterior laxity. TKA were least anterior-posterior stable at all flexion angles. In the gait lab, CPKA subjects recorded faster speeds than TKA counterparts, near-normal weight-acceptance, maximum weight-acceptance force and mid-stance forces. CPKA had longer step and stride lengths, and reported higher OKS and EQ-5D scores.

DISCUSSION: CPKA may be utilised in primary two-compartment disease or for native compartment degeneration in a knee with an existing partial knee implant, through the addition of a partial knee arthroplasty. Conservation of the ACL, healthy bone and peri-articular tissue during CPKA preserves near-native extensor efficiency, anterior-posterior stability, highly functional fast walking, good patient satisfaction and quality of life.

CONCLUSIONS: Emerging evidence suggests that CPKA may be a high-functioning, satisfying alternative to TKA in patients with multi-compartment osteoarthritis.

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Finally, to my daughter Darcie, the writing of this thesis was an unrivalled challenge during the early months of your life, but I hope one day that it may inspire you to achieve your dreams: be sure to dream big little one - I will love and support you all the way.

To my Parents

Abbreviations:

Abbreviation	Definition
ACL	Anterior Cruciate Ligament
AMOA	Anterior-Medial Osteoarthritis
A-P	Anterior-Posterior
ASA	American Society of Anaesthesiologists Score
BCA-L	Bicompartmental Arthroplasty - Lateral
BCA-M	Bicompartmental Arthroplasty - Medial
BMI	Body Mass Index
Bi-UKA	Bi-Unicondylar Knee Arthroplasty
CPKA	Combined Partial Knee Arthroplasty
CR-TKA	Posterior Cruciate-Retaining Total Knee Arthroplasty
CT	Computed Tomography
EM	Extramedullary
EQ-5D	EuroQol-5D Index of Quality of Life
GRF	Ground Reaction Force
IM	Intramedullary
ITB	Iliotibial Band
kg	Kilogram
km/h	Kilometres per hour
KOOS	Knee Injury and Osteoarthritis Outcome Score
KSS	Knee Society Score
mm	Millimetre
MRI	Magnetic Resonance Imaging
n	Number of subjects
N	Newtons
NJR	National Joint Registry
OKS	Oxford Knee Score
PCL	Posterior Cruciate Ligament
PFA	Patellofemoral Arthroplasty
PKA	Partial Knee Arthroplasty
PFJ	Patellofemoral Joint
PROMs	Patient Reported Outcome Measures

RF	Rectus Femoris
TKA	Total Knee Arthroplasty
TCA	Tri-Compartmental Knee Arthroplasty
TWS	Top Walking Speed
UKA	Unicompartmental Knee Arthroplasty
UKA-M	Medial Unicompartmental Knee Arthroplasty
UKA-L	Lateral Unicompartmental Knee Arthroplasty
VI	Vastus Intermedius
VML	Vastus Medialis Longus
VMO	Vastus Medialis Obliquus
VLL	Vastus Lateralis Longus
VLO	Vastus Lateralis Obliquus
VTE	Venous Thromboembolism
WOMAC	Western Ontario and McMaster Universities Osteoarthritis Index
yr.	Year
°	Degrees

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Thesis overview

Chapter 1 introduces the themes and research aims of the thesis

Chapter 2 describes the human knee and the treatment of end-stage OA. The history of arthroplasty is explored, along with the rationale for alternatives to TKA.

Chapter 3 introduces the concept of Compartmental Arthroplasty, and reviews the current literature

Chapter 4 investigates the language of arthroplasty and of compartmental procedures. It moves on to discuss the magnitude of further surgery following primary partial knee arthroplasty, proposing a classification system to quantify this.

Chapter 5 considers the cadaveric biomechanics of unicompartmental and combined partial knee arthroplasty. Anterior-posterior stability and extensor mechanism efficiency are investigated.

Chapter 6 investigates objective outcomes of compartmental arthroplasty through gait analysis.

Chapter 7 reviews patient reported outcomes following compartmental arthroplasty.

Chapter 8 draws the studies together, summarising the findings.

Chapter 9 considers the future of compartmental arthroplasty and avenues of interest

Chapter 10 References

Chapter 11 Appendix: discusses the impact of the work and additional documents for reference

1 Introduction

1.1 Research Motivations

By the age of 60 years, it is estimated that 10% of men and 18% of women, are affected by osteoarthritis (OA) of the knee[1] equating to more than 500 million people worldwide, 7% of the global population[2]. At its end-stage, OA results in disabling pain and loss of function which, untreated, may render the patient immobile, sleep deprived and depressed[3].

The past 160 years have witnessed an unfolding narrative of treatments attempting to rejuvenate, restore or replace the worn knee, reducing pain and returning the patient to health. Treatment of end-stage OA continues to be joint replacement. Over the past three years, 260,620 primary knee procedures were performed in the UK, of which 89.5% were 'Total Knee Arthroplasty' (TKA): replacement of all articular surfaces of the knee with metal and plastic components. In the vast majority, TKA is successful, though a much-discussed dissatisfaction rate of up to 25% persists. The knee has three compartments: the patellofemoral compartment and the medial and lateral tibiofemoral compartments. At the time of arthroplasty surgery, just 17% of patients have tricompartmental OA[4]. For the remainder, TKA inevitably results in the resection of healthy bone and peri-articular soft-tissues. Partial Knee Arthroplasty (PKA) is an alternative to TKA, selectively resurfacing the worn compartment, whilst preserving the rest. A wide body of evidence suggests PKA is safe and effective, with advantageous objective and subjective outcomes, relative to TKA, but at the expense of high revision rates[5, 6].

PKA is often unsuitable when multiple compartments are arthritic. Compartmental Arthroplasty, the use of two or more PKAs in combination (CPKA), specifically addresses the worn compartments, whilst preserving healthy bone, peri-articular soft-tissues and the cruciate ligaments. There is some evidence that CPKA is successful in the short- and medium term[7-9] but, compared to the vast body of data on TKA and PKA, relatively little is known of the biomechanical, objective and subjective outcomes of CPKA.

1.2 Research aims

The work presented in this thesis has a number of aims:

- Review the history of arthroplasty and the rationale for compartmental arthroplasty
- Unify the language of arthroplasty, with respect to the compartmental approach and the magnitude of further surgery following primary partial knee arthroplasty
- Investigate the biomechanics of partial and combined partial knee arthroplasty
- Quantify the objective and subjective outcomes of compartmental arthroplasty

1.3 Investigating Compartmental Arthroplasty

This thesis looks to examine compartmental arthroplasty as an alternative to TKA. A variety of methods can be used to investigate and compare arthroplasty procedures. Their advantages and disadvantages are described in Table 1.1

For the purposes of this thesis, a three-pronged approach has been selected:

First, the biomechanical properties of PKA and CPKA will be investigated using a cadaveric model, comparing them directly to TKA in a controlled *in vitro* environment. The intention is to ask "is there any fundamental biomechanical advantage to CPKA that justifies further *in vivo* investigation?"

The second approach considers function. It uses treadmill gait analysis to ask "compared to TKA, do patients with a CPKA demonstrate any advantage when placing high functional demands upon their knees?"

Finally, patient reported satisfaction and quality of life following CPKA are reviewed, to quantify patient's lived experience of the procedures.

Table 1.1. Research Methods used to examine joint function

Experimental Method	Definition	Advantages	Disadvantages
Human Cadaveric Studies	In vitro testing of human tissue to simulate in vivo properties	- Most realistic in terms of morphology and complex interaction of bone / soft-tissues - 'True to life' arthroplasty procedures - Wealth of existing data for comparison - Validated techniques, Repeatable - Widely accepted / believable to scientists	- Requires advanced skills in soft-tissue dissection and surgical skills - Limited number of specimens available - Limited number of implant states and repeat testing per specimen - Significant ethical considerations - Expensive / requires a specialist lab, equipment, license, tissue disposal policy - Multiple specimens required to reach significance - Time zero testing – no accounting for soft-tissue healing or rehabilitation
Animal Cadaveric Studies	In vitro testing of animal tissue to simulate in vivo properties	- Depending on animal, similar morphology to humans - Wealth of pre-existing data - Validated techniques, repeatable, believable - Cost-effective alternative to human tissue - Greater availability of specimens Vs. humans	- Not well suited to arthroplasty - lack of animal-specific implants - Where procedures are possible, limitations in application of data to humans - Ethical considerations (though less so than for humans) - Time zero testing - Resource heavy – requires specialised lab, equipment and license
Staged Animal Studies	Stage 1: live animal procedure / experiment Stage 2: post-mortem testing	- Good representation of bone or soft-tissue adaptation to procedure over time - Realistic post-operative testing in living species - More repeatable than in humans / greater range of tests possible - Combination of in vivo, ex vivo and in vitro experimentation possible - Some validation of existing techniques	- Not well suited to arthroplasty: Where procedures are possible, limitations in application of data to humans - Ethical considerations - Very resource heavy – requires specialised operating theatre and surgeons / veterinarians / technicians, animal house or accommodation of live animals following procedure, recourses for animal sacrifice, separate cadaveric lab, equipment and license
Finite Element Analysis	In silico mathematical modelling of discrete parts of system	- Relatively inexpensive - Able to generate large quantities of data, Repeatable and Reproducible - Infinite number of potential implant states - Requires only a software package (no need for labs or specialised equipment) - Minimal ethical considerations - Solves a specific problem	- Requires input of specific data to create boundary values - Vulnerable to significant error if input data is incorrect - Requires a skilled operator with specialist knowledge of the problem, the technique and the mathematics behind the algorithms. - Some scepticism amongst scientific community as to validity of data - Large gap from "bench to bedside"
Fabricated Modelling	Synthetic models representing bones or soft tissues, e.g. sawbones	- Inexpensive - Repeatable and Reproducible - Excellent for "bone only" models (pull-out strength / impaction / wear etc.) - Can easily demonstrate / learn / practice new techniques - Requires only basic laboratory conditions - No ethical considerations	- No representation of interaction between soft-tissues and bones, therefore difficult to recreate in vivo anatomy. - Of limited use for dynamic testing - Some scepticism amongst scientific community as to validity of data - May require surgical skill for accurate bone handling / implant positioning - Often uses the same bone model – no variability between subjects, limiting broad application of the data.

Instrumented Implants	Modified prostheses to include pressure sensors or strain gauges (e.g. OrthoLoad)	- High-quality realistic and reproducible data - Most likely to represent "ground truth" - Dynamic – can conduct a broad range of tests / activities depending on the capability of the participant - Can capture data over time – constantly evolving depending on question - Vast quantity of data available	- Only suitable for implanted arthroplasty states – cannot compare to the native knee - Ethical considerations - Potential for "drop out" of participants - Implications of implant modification (may lead to bio-toxicity / possible radiation depending on material used / altered implant strength or tissue interaction - Difficult to retrieve / maintain if device fails - At present requires interval monitoring, only when external data recording devices attached - No remote data collection possible currently – limited by inability to implant a power supply to the device - Time delay between technological advance and device modification / data output
Clinical Trials	In vivo studies comparing one procedure with another	- Direct in vivo comparison of devices in matched cohorts. - Specific outcomes established by the trial protocol - Can be multi-centre - Opportunity for equipoise (whereby surgeons are paired to perform the procedure they're most comfortable or familiar with)	- Requires adequate power which, for comparison of arthroplasty subjects, can necessitate large study groups. - Expensive - Time consuming: may be many years before outcomes are reported - Matching may not account for confounding factors and/or fundamental differences between subjects
Patient Reported Outcome Measures	Questionnaires and surveys on satisfaction, quality of life and subjective function	- Repeatable at specific time points before and after surgery - Can record a moment in time or change over time - Relatively inexpensive - Straightforward comparison of numbers - Inter- and intra-patient comparisons possible	- Subjective, can vary from one day to the next - Ceiling effect in the best responders, floor effect in the worst - Multiple different scoring systems, all with their own advantages and disadvantages - Time consuming for patients – response fatigue - Does not take account of co-morbidities or other patient factors - Statistical power usually requires large sample groups - Statistical differences do not always equate to minimal important clinical differences
Gait Analysis (Traditional)	Measurement of Ground Reaction Forces and temporospatial analysis as subject walks over force plates in floor	- Most realistic form of walking – true to life - Can modify the force plates as technology evolves - Repeatable / reliable / reproducible - Can test healthy subjects as controls - Relatively little training required to collect accurate data – can be conducted by a technician with limited knowledge of the procedures - Can easily combine with motion capture analysis	- Captures only a small number of steps per cycle - Difficult to quantify and control changes in speed / slope - Requires a large space with reinforced / modified floor - Limited ability to adapt - Ethical implications - Subjects may alter / modify their walking as a product of "being watched" - Can be burdensome for patients.
Gait Analysis (Treadmill)	Measurement of Ground Reaction Forces and temporospatial measurement on an instrumented treadmill (force plates beneath moving belt)	- Repeatable and reproducible - Broad spectrum of data available - Can test healthy subjects as controls - Can facilitate measurement at different speeds / uphill and downhill - Requires only a small space for data collection - Relatively little training required to collect accurate data – can be conducted by a technician with limited knowledge of the procedures - Can capture a very high number of steps compared to traditional gait lab – more likely to represent a fair "average"	- Ethical implications for subject participation - Safety concerns for elderly participants with comorbidities: cardiac stress for example - Can induce or exacerbate pain / fear of falling - Requires specialist equipment – expensive start-up costs - May be expensive / difficult to keep up with evolving technologies - Some debate as to how representative treadmill walking is of walking on the ground - Possible to exert patients beyond what they normally do – may not represent "real life" activity or function. - Subject may be susceptible to fatigue, altering gait - More difficult to combine with motion capture

Motion Capture	Sensors placed at specific anatomical landmarks on the subject or specimen, then tracked and recorded as movement occurs, to create a 'virtual skeleton'	- Captures dynamic movement - Possible to analyse 'whole system' and individual parts - Accurate kinematic data - Reproducible - Wide range of data available - Can be performed on live subjects (human or animal), cadavers and fabricated models - Can be combined with other testing techniques / modalities - Widely accepted / validated and believed by scientific community	- Technically difficult: vulnerable to errors in bone/soft-tissue registration, movement of markers - Markers on skin are 'distant' from the bony landmark they represent, can introduce errors. - Based on a model of the skeleton: many missing parts, accuracy relies on the quality of data input to the original model - Expensive equipment costs - Requires adequate testing space - Wide ranges of movement may require multiple motion-capture cameras to avoid 'drop out' of data
Radiological Imaging	Plain film radiographs, computer tomography (CT) or Magnetic Resonance Imaging (MRI)	- Ability to image the joint in two (plain film X-Ray) or three (CT / MRI) dimensions, to determine implant position in relation to the native anatomy and any subsequent bony or soft tissue changes - Widely available, relatively inexpensive, relatively easy to interpret - Widely accepted / validated and believed by scientific community - Can be performed on live subjects and cadavers	- Provides only limited research data – usually as part of data gathering for use with another modality - Captures a static "moment in time" – can be misleading as to the dynamic state of the joint or situation if the knee if the scan is repeated with the joint in a different position - Typically, non-weight bearing - Radiation dose to the subject – ethical considerations -
Dynamic Radiological Imaging	Single or multi-plane) performed as the subject moves (walking, squats etc).	- Real time weight-bearing motion analysis - Can test over a wide range of activities - Can compare pre- and post-surgery and include healthy controls - Widely accepted by scientific community, validated techniques	- Radiation dose to the subject – ethical considerations - Some evidence subjects deviate from their normal motion, as a consequence of laboratory testing environment - Resource heavy: expensive equipment / start-up and maintenance costs - Large laboratory space required, with additional building regulations for radiation protection of staff and neighbouring rooms - Risk of exacerbating pain

2 The Human Knee Joint

2.1 Anatomy

The knee is a modified hinge, a typical synovial joint. Composed of three separate functional compartments, the knee is the site of articulation between the femur, the tibia and the patella. The tibiofemoral articulation consists of medial and lateral compartments, separated centrally by the tibial spines, the intercondylar notch and the cruciate ligaments. The patellofemoral articulation forms the third compartment.

2.1.1 The Tibiofemoral Joint

The tibiofemoral joint is the articulation between the medial and lateral femoral condyles, and the tibial plateau. Distally, the femoral shaft broadens to form the medial and lateral condyles, separated by the trochlear groove, which articulates with the patella. Of the two condyles, the medial is larger, more curved, elongated and oval, whereas the lateral condyle is smaller[10] (Figure 2.1). The transepicondylar axis is typically 3° externally rotated relative to the posterior condylar axis. From the axial view, the anterior cortex has a flange, more prominent laterally, which supports patella tracking during flexion and extension.

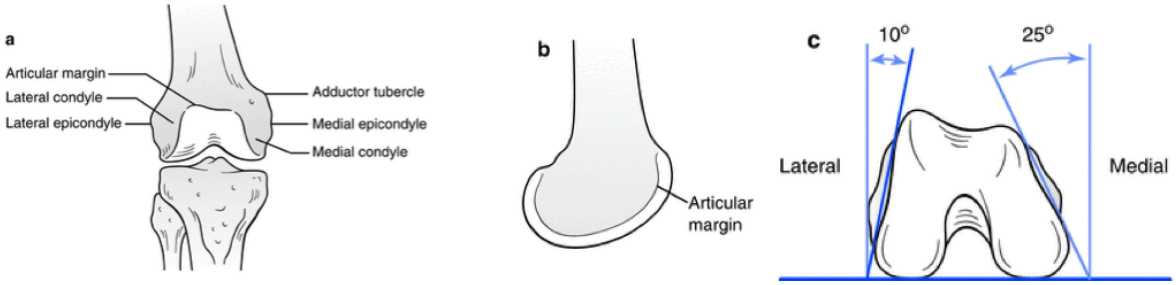


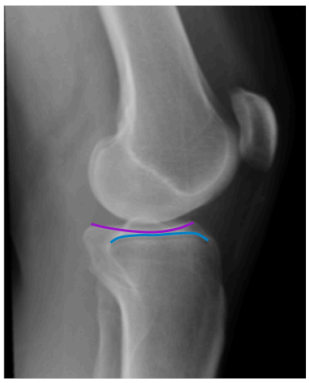
Figure 2.1. Anatomy of the distal femur (a) Anterior view (b) Medial view (c) Axial view from distal perspective annotated to demonstrate the anterior surface sloping distal from lateral to medial, with a lateral wall inclination of 10° and a medial wall in inclination of 25°

Reprinted from "Distal Femur Fractures" Arun Aneja, Matt L Graves. Copyright 2015, with permission from Springer Nature[10]

The epicondyles give rise to the collateral ligaments: At terminal extension both the medial collateral ligament (MCL) and lateral collateral ligament (LCL) are tight, conferring varus/valgus stability. As the

knee flexes, the LCL becomes lax and the lateral compartment may open up to 6.7° with the application of varus stress, whilst the MCL remains tight and the medial joint opens by just 2.1mm.

The plateau of the medial compartment is a concave sliding ball and socket with a 7 – 11° posterior sagittal slope. The lateral plateau is convex, with a posterior slope of 4 – 8° (Figure 2.2) [11-15]. In the coronal plane, the tibia slopes upwards laterally, at an angle of 2.5 ± 1.9°in women, and 3.5 ± 1.9° in men (p=0.03)[16].



	Medial	Lateral
Articular Surface	Concave	Convex
Relative Size	Large	Small
Cartilage thickness	3mm	4mm
Posterior Slope	~ 10°	~ 7°
Meniscus	Circular More peripheral Attached to MCL	C-Shape Wider, more coverage Attached to PCL

Figure 2.2. Lateral Radiograph of the knee annotated with the medial (purple) and lateral (blue) tibial plateau and table comparing the medial with lateral tibial plateau.

Radiograph reproduced with permission

The morphological and functional asymmetry between the medial and lateral compartments becomes relevant when considering joint restoration, reconstruction and replacement. The design and evolution of knee replacement is discussed in chapter 2.6 “The History of Arthroplasty”, with much development occurring in the 1960s-1990s. At that time there was much development of the four-bar linkage concept, that remains relevant to contemporary arthroplasty. The Anterior Cruciate Ligament (ACL), Posterior Cruciate Ligament (PCL), distal femur and tibial plateau form the four elements, joined within a closed loop system, resulting in a combination of sliding and rolling motion. With flexion, the medial and lateral condyles roll back across the tibia, subsequently rolling forwards during extension[17]. An alternative concept had been suggested in 1941 by Brantigan and Vishell[18]. They reported that the lateral femoral condyle was the main source of roll-back, rotating around the relatively static medial femoral condyle. The difference in femoral condylar shape is significant, such that in the sagittal plane the medial femoral condyle is circular posteriorly, with a radius of approximately 22mm, and an arc of 110° (Figure 2.3). The anterior articular surface is known as the “extension facet”, and has a radius of 32mm. Hence, the centre of rotation in flexion shifts posterior-distally in the sagittal plane, creating two distinct radii. The medial femoral condylar

facets are congruent with the medial tibial plateau. Meanwhile, the lateral femur has a radius of 21mm, rotating around an arc of 114°. The lateral flexion facet is long and well-defined, whilst the lateral extension facet is short and variable.

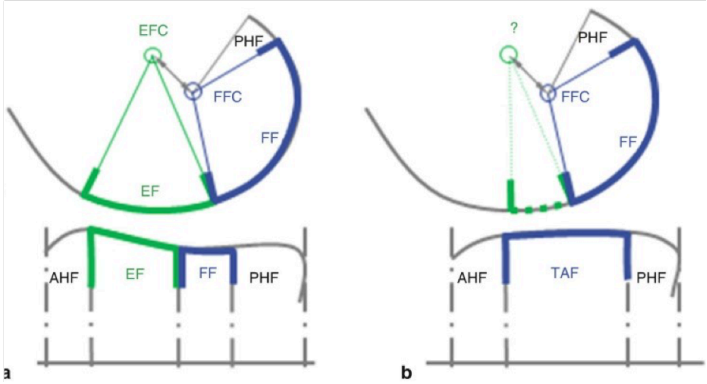


Figure 2.3. Diagram of the sagittal section through the centre of the medial (a) and lateral (b) tibiofemoral compartments.

Reproduced from Pinskerova V., Vavrik P. (2020) "Knee Anatomy and Biomechanics and its Relevance to Knee Replacement". In: Rivière C., Vendittoli PA. (eds) "Personalized Hip and Knee Joint Replacement". Springer, Cham. Under the Creative Commons CC BY License

The divergent posterior tibial slopes, in part, facilitate femoral roll back in deep flexion: the lateral femoral condyle pivots about the medial condyle, moving on average 20mm in the anterior-posterior plane, over an arc of 0-120° of flexion, whilst the medial condyle rolls posteriorly in flexion, against the anterior sliding effect, moving only 1.5mm posterior beyond 120° of flexion (Figure 2.4)[19-21].

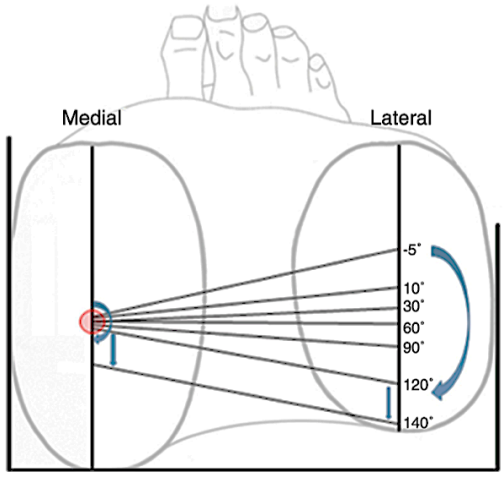


Figure 2.4. Axial diagram of the tibia looking distally. The lines relate to the centre of the condyles during flexion from -5° to 140°.

Reproduced from Pinskerova V., Vavrik P. (2020) "Knee Anatomy and Biomechanics and its Relevance to Knee Replacement". In: Rivière C., Vendittoli PA. (eds) "Personalized Hip and Knee Joint Replacement". Springer, Cham. Under the Creative Commons CC BY License[22]

Lateral femoral roll back around the sliding medial femoral condyle results in internal rotation of the tibia during flexion and external rotation during extension[20]. External rotation of the tibia and tension of the cruciate ligaments in terminal extension is referred to as the 'screw home mechanism' and results in stabilisation of the knee during heel strike.

2.1.2 The Menisci

The menisci are two fibrocartilaginous crescent-shaped wedges (from the Ancient Greek word μηνίσκος, meniskos, meaning "crescent") which sit within the tibiofemoral joints. Within the medial compartment, the meniscus covers ~60% of the articular surface, whilst the C-shaped lateral meniscus covers ~80%[23] (Figure 2.5).

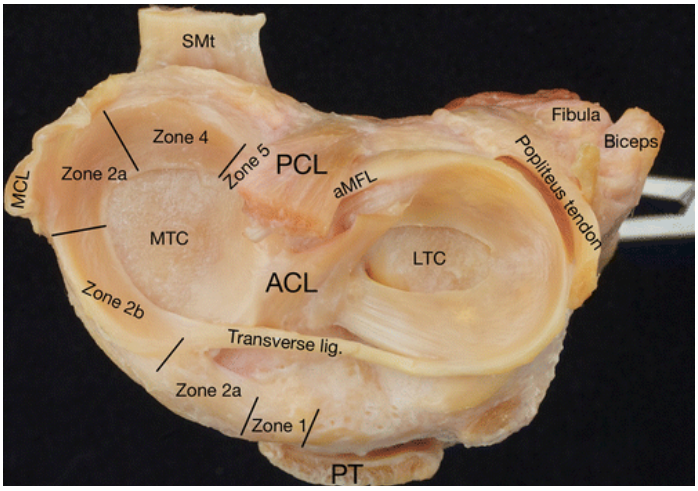


Figure 2.5. Cadaveric axial view of the left knee tibial plateau (abbreviations as per thesis introduction)

Reprinted with permission from "Meniscus Anatomy" Urszula Zdanowicz, Robert Śmigielski from "The Menisci" ed. Robert F. LaPrade, Elizabeth A. Arendt, Alan Getgood, Scott C. Faucett. Copyright (2017) with permission from Springer Nature.[24]

Once considered vestigial remnants of muscle within the knee[25], the menisci are now known to have a number of important functions including acting as shock-absorbers[26], increasing joint congruency and reducing point loading by dissipating the load across wider contact areas, thereby sharing the load with the bony surfaces[27]. It has been suggested that the menisci have a role in knee proprioception[28], nutrition of articular cartilage [29] and joint lubrication[29]. There is good evidence that the medial meniscus is a secondary stabiliser of anterior-posterior laxity[30, 31]. In the absence of the ACL, anterior tibial loads significantly increase the resultant forces in the medial meniscus during flexion[29]. Medial meniscectomy in the ACL-deficient knee results in a significant increase in anterior

tibial translation of up to 6mm in mid-flexion, as a consequence of the increased anterior tibial loads, suggesting that the medial meniscus contributes towards anterior-posterior stability of the knee, as an adjunct to the ACL, in part due to being anchored to the MCL[29] (Figure 2.6). The medial meniscus is confluent with the MCL, contributing towards medial congruity.

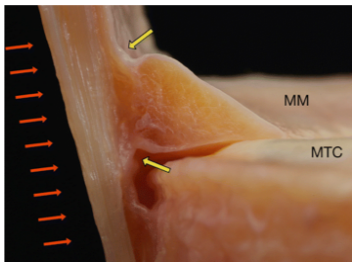


Figure 2.6. Cadaveric coronal section of the wedge-shaped medial meniscus (MM) sitting on the medial tibial condyle (MTC) demonstrating confluence of its fibres with the medial collateral ligament (demarcated by red arrows)

Reprinted with permission from "Meniscus Anatomy" Urszula Zdanowicz, Robert Śmigielski from "The Menisci" ed. Robert F. LaPrade, Elizabeth A. Arendt, Alan Getgood, Scott C. Faucett. Copyright (2017) with permission from Springer Nature.[24]

The lateral meniscus is mobile, moving posteriorly over the tibial plateau in deep flexion, as the femur rolls back. The role of the lateral meniscus in stabilisation of the knee is difficult to discern[31]. In very deep flexion, the lateral femoral condyle rolls over the posterior rim of the tibia, lifting off of the tibial plateau anteriorly but maintaining contact with the posteriorly-translated meniscus, meanwhile the medial meniscus remains anchored.

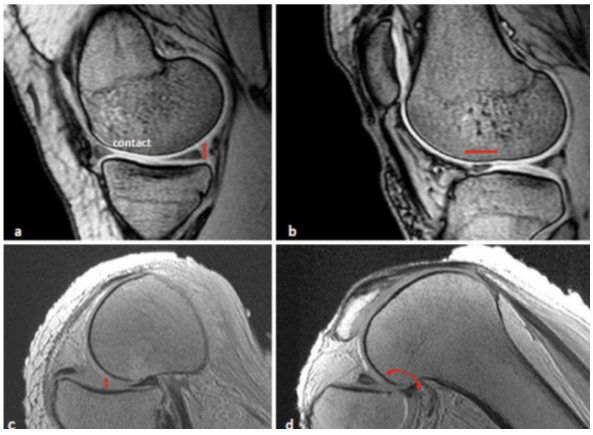


Figure 2.7. Sagittal MRI in hyper-extension through the medial (a) and lateral (b) compartments and in deep flexion medial (c) and lateral (d)

Reproduced from Pinskerova V. Vavrik P. (2020) "Knee Anatomy and Biomechanics and its Relevance to Knee Replacement". In: Rivière C. Vendittoli PA. (eds) "Personalized Hip and Knee Joint Replacement". Springer, Cham. Under the Creative Commons CC BY License[22]

Meniscal tears may occur during acute knee injury or as a consequence of arthrosis. They are the most common injury of the knee[32]. Medial tears occur twice as often as lateral tears[33]. In the short-term, resection of the damaged meniscus can result in rapid reduction in pain and restoration of function[34]. Meniscectomy, either total or partial, has been a feature of the knee surgeon's tool kit for more than a century. However, as the important role of the menisci have been greater understood, so too have the consequences of meniscectomy[35-39]. The seminal study by Baratz, Fu and Mengato[40] in 1986 used cadaveric knees to demonstrate that total medial meniscectomy reduced the contact area by 75% whilst increasing peak contact pressure by 235%, with the inevitable consequence of articular cartilage 'overload', leading to failure[41]. Burke, Ahmed and Miller[42] demonstrated a linear correlation between the extent of meniscal resection and the increase in joint surface peak stress. The advent of arthroscopic surgery in the 1970s and subsequent widespread adoption facilitated more conservative partial meniscectomy and a raft of studies comparing total with partial meniscectomy with a realization that medium to long-term resultant knee function was inversely proportional to the amount of meniscal tissue resected[43-47].

Such is the importance of the menisci, that modern practice advocates meniscal repair where possible, and preservation of meniscal tissue, except where resection is unavoidable. In his 1980 Journal of Bone and Joint Surgery, entitled "He who hesitates is saved", Goodfellow stated that "Meniscectomy is only justifiable if a meniscus is causing more trouble than it is worth, and that is a value judgement which, like much else in clinical surgery, must be taken on inadequate evidence". Goodfellow's partial knee replacement philosophy relied, in part, on retention of the healthy meniscus in the native compartment, otherwise sacrificed in total knee replacement.

2.1.3 The Patellofemoral Joint

The patella (from the Latin, 'small plate') is the largest sesamoid bone in the body and sits anterior to the femur, within the quadriceps tendon. Its posterior cartilaginous surface is divided in the sagittal plane into medial and lateral facets, which articulate with the femur sliding through the trochlear groove during flexion and extension. The patella acts as a complex lever, its fulcrum being the patellofemoral contact area, the patellofemoral joint (PFJ). As the knee passes through its arc of motion, this fulcrum magnifies the moment arm of the extensor mechanism. The knee extensor mechanism influences general locomotion through gait efficiency, chair rising and stair climbing.

Patella geometry has a significant impact on the development of PFJ OA. Wiberg classified the geometry according to three groups: Type 1, equal medial and lateral facets; Type 2, concave lateral facet, smaller concave medial facet and Type 3, even smaller convex medial facet[48]. Wiberg Type 3 individuals are more likely to develop PFJ OA, due to uneven distribution of load and high contact stress in the lateral facet. PFJ contact pressure is typically 0.5 x body weight during level walking, but rises to 2.5-3.3 x body weight during stair ascent and descent[49].

2.1.4 Lower Limb Alignment

The femur and the tibia act as large lever arms about the knee joint, resulting in loading moments, responsible for mechanical stress. Consequently, loads of 2-4 times body weight are transmitted through the tibiofemoral joint during level-ground walking, rising to 4.25 times body weight during stair climbing[50]. This has significance for articular cartilage wear, especially if the alignment of the limb deviates significantly from normal, resulting in uneven wear and worsening deformity.

Lower limb alignment, in the coronal, sagittal or axial planes, is described in relation to the mechanical longitudinal axis, or Mikulicz line, which passes between the centre of rotation of the femoral head, to the centre of the ankle. Where this line crosses the knee is relevant for distribution of load and resultant compartmental wear. Normal alignment sees the mechanical axis pass through the knee approximately 4 ± 2mm medial to the centre of the tibial eminence. The anatomical axis follows the diaphyseal midline of the long bones. Whilst the tibial anatomical axis is largely parallel to the mechanical axis, the shape of the femur results in divergence of its anatomical axis from the mechanical axis by approximately 6°. Hence, in normal axial alignment, the femoral-tibial angle is typically 174°. Divergence from the normal femoral-tibial angle is considered misalignment. In cases where the centre of the knee joint is lateral to the mechanical axis, alignment is described as genu varum, resulting in abnormal load distribution through the medial compartment. In genu valgum, the centre of the knee is medial to the mechanical axis, resulting in abnormal lateral compartment loads. Typical femoral valgus angles are mean 83.3°, a reduction to mean 80.7° is sufficient to lateralise the coronal weight-bearing axis, leading to disproportionate lateral wear[51]. Morphological differences at the hip can have a similar effect, including adduction deformities, reduced offset and coxa valga[52].

2.2 Movement of the knee joint

The knee joint has six degrees of freedom: three rotations (Internal/External, Varus/Valgus and Flexion/Extension) and three translations (Anterior/Posterior, Medial/Lateral and Superior/Inferior). (Figure 2.8):

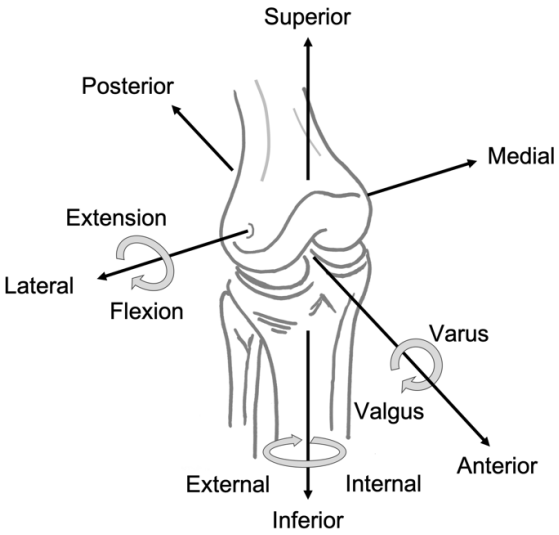


Figure 2.8.The six degrees of freedom of the knee joint

Muscles of the thigh control movement of the knee joint, including flexion, extension and the 'screw home' mechanism. The actions and locations of the muscles are shown in Figure 2.9 and Table 2.1.

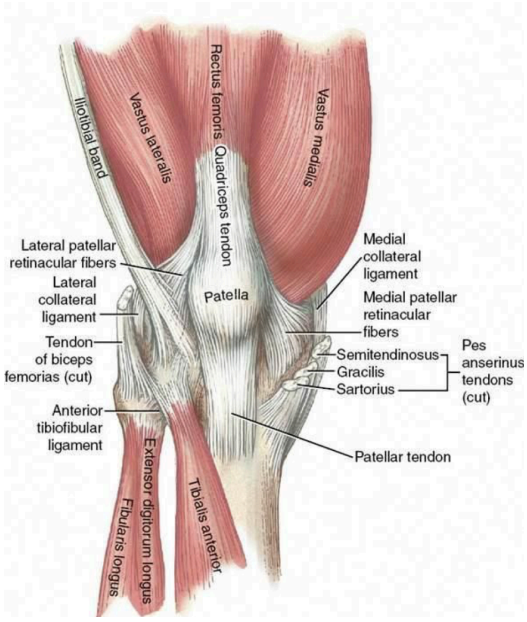


Figure 2.9. Anatomy of the Knee from the anterior aspect

Reproduced from" Comparative Kinesiology of the Human Body". Chapter 22 – Kinesiology of the knee joint. Gulcan Harput. Pages 393-410 Copyright (2020), CCC with permission from Elsevier[53]

	Structure	Action	Origin	Insertion	Nerve
Anterior	Rectus Femoris (RF)	Knee Extension (weak) Hip Flexion	Straight Head: Anterior Inferior Iliac Spine (ASIS). Reflected Head: Groove superior to Acetabulum	Quad. femoris tendon	Femoral
	Vastus Medialis (VM) Longus (VML). Proximal Obliquus (VMO). Distal	Knee Extension	Anteromedial proximal femur (intertrochanteric line)		
	Vastus Intermedius (VI)	Knee Extension	Anterolateral proximal femur deep to VL		
	Vastus Lateralis (VL) Longus (VLL). Proximal Obliquus (VLO). Distal	Knee Extension	Anterolateral proximal femur / lateral half intertrochanteric line		
	Sartorius	Knee Flexion (weak), Tibial internal rotation Hip Flexion / Lat. Rotation	Anterior Superior Iliac Spine	Pes anserinus	Femoral
	Tensor Fascia Lata (TFL)	Knee Stabiliser in Extension	Iliac Crest	Iliotibial band	Sup. Gluteal (L4-L5)
Posterior	Biceps Femoris	Knee Flexion Tibial External Rotation	Long Head: Ischial tuberosity Short Head: Linea Aspera	Fibula Head	Sciatic
	Semitendinosus	Knee Flexion Tibial Internal Rotation. Hip Extension	Ischial Tuberosity	Pes anserinus	Sciatic
	Semimembranosus	Knee Flexion, Med. rotation of leg at knee. Hip Extension	Ischial Tuberosity	Medial tibial condyle	Sciatic
Medial	Gracilis	Knee Flexion Tibial Internal Rotation, Hip adduction	Inferior pubic ramus, pubis	Pes anserinus	Obturator

Table 2.1. Muscles acting about the knee joint

The ‘extensor mechanism’ of the knee includes the quadriceps muscles and their resulting tendon, the medial and lateral retinacula; the patella; patellar tendon and tibial tubercle (Figure 2.9). The synergistic action of these structures results in controlled knee extension; stability and power, affecting functions including fast walking; slope and stair ascent and descent and chair rising. Anchored within the trochlear groove by the quadriceps tendon proximally and the patellar tendon distally, the patella improves the efficiency of the extensor moment arm by acting as a fulcrum.

The medial and lateral retinacula provide rotational stability for the patella, whilst the bony geometry, vastus medialis, the medial collateral, patellofemoral, patello-tibial and medial patello-meniscal ligaments prevent its lateral displacement during flexion. Lateral structures are less distinct, consisting of arciform fibres from the anterior expansion of the iliotibial band, which blend with the fascia lata and interdigitate with longitudinal fibres of vastus lateralis to cover the patella[54]. The joint capsule is thickened laterally to become the lateral patellofemoral ligament, which anchors the patella to the lateral femoral epicondyle, though its presence is variable, as is that of patello-meniscal ligament[54]

The hamstring muscles are responsible for knee flexion, crossing the hip and knee in the posterior thigh compartment. Gracillis (medial compartment) and Sartorius (anterior compartment) contribute toward knee flexion, whilst Semitendinosius, Semimembranosus and the long head of biceps femoris extend the hip. The hamstrings antagonise the quadriceps muscles, decelerating knee extension. Posterior stability is the product of the actions of the hamstring muscles; the medial and lateral heads of gastrocnemius which stabilise the posterior capsule, and the popliteus muscle, which augments the posterior cruciate ligament.

2.2.1.1 The Anterior Cruciate Ligament

Then anterior cruciate ligament (ACL) is an intracapsular, extra-synovial ligament of the knee, which originates on the medial border of the lateral femoral condyle, demarcated by the lateral intercondylar ridge[55]. On the tibial plateau, the ACL creates a broad and irregular anterior attachment between the intercondylar eminences[56]. The ACL is approximately 33mm in length, its primary function is to resist anterior-lateral displacement of the tibia on the femur, whilst at 0° of flexion, it resists varus displacement. It has significant tensile strength, up to mean 1550 $\pm$ 620 N in one cadaveric study[57].

The ACL consists of two bundles, separated at their femoral origin by the bifurcate ridge:

- The anteromedial bundle is the primary restraint to anterior tibial translation measured clinically using the anterior drawer test. It is tight in flexion, when the fibres are externally rotated, and loose in extension, when the fibres run parallel to each other along the length of the ligament.
- The posterolateral bundle is primarily responsible for rotational stability, preventing internal tibial rotation towards terminal extension[58]. Its fibres are tight in extension and loose in flexion.

2.2.1.1.1 Anterior Cruciate Ligament Innervation and Role in Stability of the Knee

The ACL is fundamental to knee stability and function[59-61]. Extensively innervated, the ACL provides proprioception and feedback, modulating muscle function and stability during loading. ACL trauma and its management are beyond the scope of this thesis, though it is noteworthy that ACL injury

leads to anterior-lateral rotatory instability. Chronic ACL deficiency can result in early-onset rapid progression of posttraumatic OA[62].

Primary end-stage OA, typically in the elderly, can result in ACL dysfunction[63], though the majority have an intact, functional ACL: in one series, ACL integrity was assessed prior to resection at the time of arthroplasty surgery and revealed that 78% of cases sacrificed an intact, functional ACL as part of the standard TKA procedure[64, 65]. Another study of 300 consecutive patients undergoing TKA for Kellgren-Lawrence grade ≥ 3, revealed that the ACL was intact in 55% of patients, frayed in 27%, and disrupted or absent in the remaining[66]. The central location of the ACL attachment on the tibial plateau makes preservation challenging during joint replacement.

2.2.1.2 Posterior Cruciate Ligament

The PCL resists up to 2500 N of posterior tibial displacement, relative to the femur during flexion, and varus displacement of the tibia during extension. Like the ACL, the PCL is intracapsular but extra-synovial, originating on the lateral border of the medial femoral condyle, and inserting posterior to the ACL on the tibial plateau, in the tibial sulcus. It consists of two bundles: the anterior-lateral bundle is shorter, thicker and stronger, whilst the posterior-medial bundle is longer, thinner and weaker. On the femur, the bundles of the PCL are separated by the medial bifurcate ridge, and the proximal border of the PCL attachment is marked by the medial intercondylar ridge.

2.3 Osteoarthritis and Arthroplasty Surgery

Osteoarthritis (OA) is a degenerative disease of the synovial joint causing progressive loss of articular cartilage, resulting in reduced joint space, osteophyte formation, subchondral bone cysts, lytic lesions and sclerosis. Symptoms include pain, swelling, stiffness, and mechanical symptoms including locking, catching or instability. Asymmetrical joint surface wear results in progressive limb misalignment and altered function.

The lifetime risk of developing OA of the knee is estimated at 44.7%, rising to 56.8% following knee injury [67]. Aetiology is multi-factorial, and includes advancing age, female gender, history of trauma and excess body weight. Those with a Body Mass Index (BMI) >25 Kg/m^2 have a 46.9% lifetime risk of developing gonarthrosis, rising to 60.5% when the BMI >30 Kg/m^2 .[67] Radiographic prevalence of gonarthrosis is 19.2% - 27.8% in those over 45 years old (yrs.) and 37% of those >60yrs [68]. In 1994, the Framingham study assessed the disabling effects of common medical conditions in the elderly, when controlling for sex, comorbidity and age. Of the 1769 non-institutionalised participants, OA of the knee was as disabling as significant cardiac disease and chronic obstructive pulmonary disease, when undertaking basic functional activities and independent living[69]. The socioeconomic burden of OA is significant, costing between 1.0% - 2.5% of gross domestic product of developed countries across the world[70]. Waiting times for knee surgery have increased substantially during the COVID-19 pandemic, with some patients waiting up to two years for surgery. Each additional month spent waiting for surgery results in a significant deterioration in quality of life[71].

2.4 Treatment of End-Stage Osteoarthritis

OA is typically a non-uniform phenomenon, commonly affecting a single compartment of the knee, but may present with two or even three compartments affected. Wear to the medial tibiofemoral compartment is ten-times more common than that in the lateral tibiofemoral compartment, primary PFJ arthrosis is least common[72, 73]. Bicompartmental (PFJ with one tibiofemoral compartment) disease is present in 59% of those with gonarthrosis [74]. In one study, 40% of patients over 50 years old with knee pain had radiographic evidence of combined medial and PFJ wear, 24% had isolated PFJ arthrosis, whilst only 4% had isolated tibiofemoral arthrosis [75]. Degeneration of all three compartments simultaneously is rare[73]. A recent systematic review and meta-analysis from our group suggested that OA is confined to a single compartment in 50% of those with end-stage disease (Figure 2.10), most commonly affecting the medial tibiofemoral compartment (27%) with isolated

lateral disease least common (5%)[4]. A third of patients have two-compartment disease, of which medial with patellofemoral compartment OA is the most common pattern (23%). Tricompartmental OA is found in just 17% of those at the time of arthroplasty surgery[4] (Figure 2.10).

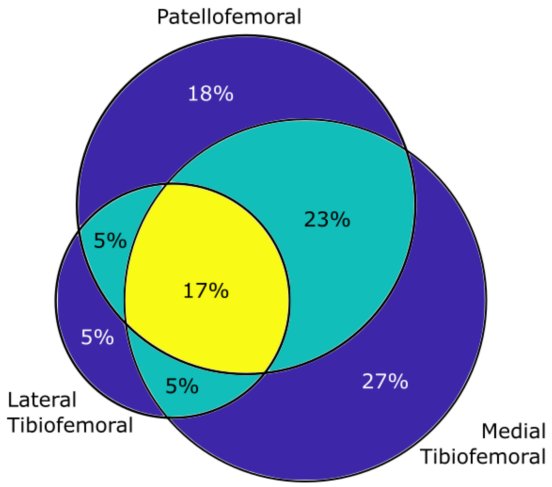


Figure 2.10. Distribution, by compartment, of end-stage osteoarthritis of the knee.

Taken directly from Stoddart et. al Osteoarthritis and Cartilage[4] with permission.
A. Garner role in systematic review – conceptualisation of the study, review and editing of the manuscript, otherwise as per authorship of paper.

In 2021, OA was the sole indication for knee replacement in 96.6% of cases[76]. Joint replacement remains the standard of treatment for end-stage OA. The basic principles of arthroplasty involve resection of the diseased cartilaginous joint surfaces, through a series of bone cuts, which are then replaced, typically with metallic components, separated by a plastic insert or bearing. Contemporary arthroplasty of the knee broadly falls into two categories, Total Knee Arthroplasty (TKA) and Partial Knee Arthroplasty (PKA). Each will be discussed, however, the fundamental difference between them is that TKA involves resurfacing the entire distal femur and the tibial plateaux, necessitating resection of the medial and lateral menisci, and, depending on the design of the implant, usually also the ACL. In some designs, the PCL is also resected. The articular surface of the patella may be resurfaced.

PKA involves selective resection and resurfacing by compartment, targeted toward the pattern of wear. The healthy remaining articular surfaces, peri-articular soft-tissues and the cruciate ligaments are preserved. Tibiofemoral PKA is referred to as unicompartmental knee arthroplasty (UKA) and may be medial (UKA-M) or lateral (UKA-L). Patellofemoral arthroplasty (PFA) is the selective

resurfacing of the trochlear groove with a metallic component and resurfacing of the articular surface of the patella with a polyethylene 'button'.

PKA may be implanted in isolation for single compartment OA or used in combination for multi-compartment wear. This thesis focuses on 'Compartmental Arthroplasty' and the use of 'Combined Partial Knee Arthroplasty' (CPKA), two or more PKA implants within the same knee. The nomenclature of these combinations is discussed in detail in Chapter 4 The Language of Arthroplasty. However, based on that data, the combinations will be referred to, throughout the text as 'bicompartmental arthroplasty' (BCA) to denote the combination of PFA with UKA of either the medial (BCA-M) or lateral (BCA-L) compartments and 'bi-unicondylar arthroplasty' (Bi-UKA) when describing the use of a medial and lateral UKA in combination[77]. The use of a medial UKA, lateral UKA and PFA in the same knee is referred to as a 'tricompartmental arthroplasty' (TCA). TCA will not be discussed in any great detail in this thesis. However, some patients excluded from gait analysis in Chapter 6 were subsequently revised to TCA through the addition of a third PKA, hence it is mentioned in passing.

The number of primary arthroplasty procedures performed in the United Kingdom in 2020 was dramatically reduced as a consequence of the COVID-19 pandemic. Therefore, the 2021 National Joint Registry (NJR) report detailed a three year average of arthroplasty procedures (1st January 2018 – 31st December 2020)[76]. During that time, 260,620 primary knee procedures were recorded, of which 89.5% were TKA, 9.3% were UKA (medial and lateral) and 1.2% were PFA. Of the TKAs, 68.7% received cemented, unconstrained, fixed bearing devices, whilst 61.5% of UKA patients received a mobile bearing device[76]. 56.3% of arthroplasty patients were women. Median age at primary TKA were 70yrs (IQR 63 – 76), whilst PKA and CPKA were, on average, 6-12 yrs. younger[76].

2.6 The History of Arthroplasty

To improve knee replacement outcomes, we must first understand the history of arthroplasty. In the 1800s it had been recognised that knee cartilage wear resulted pain and stiffness. By the 1860s, Verneil and others were attempting to reconstruct worn cartilage using a variety of synthetic and biological materials, including nylon, cellophane, capsule, fascia lata, prepatellar bursa and porcine bladder, with universally poor outcomes. Excision arthroplasty increased range of movement in the short-term, but ultimately led to ankylosis and poor function. By 1891, Themistocles Gluck had implanted a 17-year-old girl with a primitive Ivory hinge (Figure 2.11). The initial outcome was successful, but short lived, with chronic joint infection leading to failure.

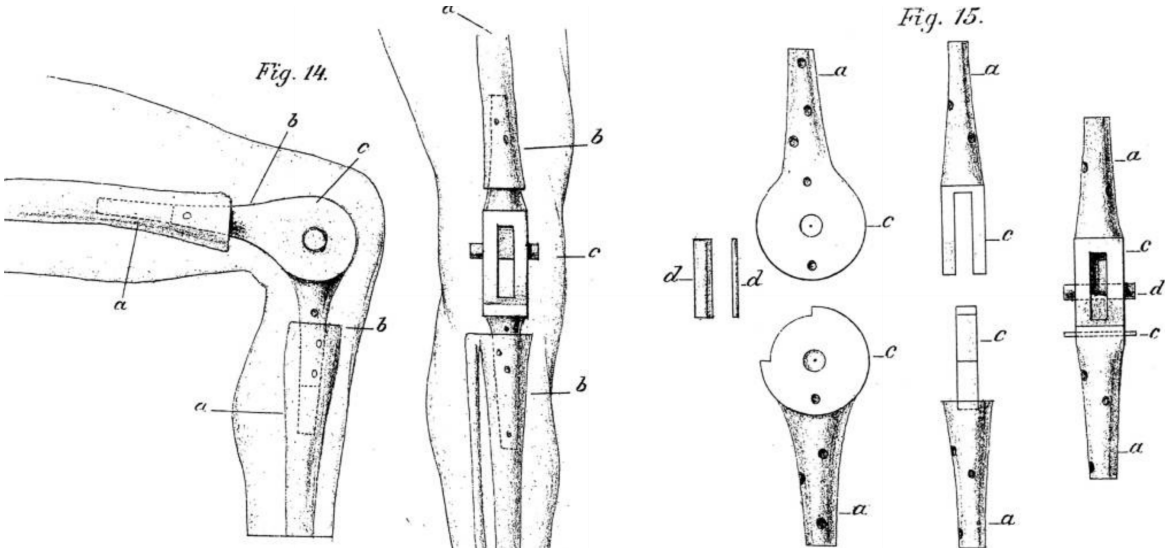


Figure 2.11.The Gluck Ivory Knee

Reproduced from "Themistocles Gluck: an unrecognised genius. Eynon-Lewis, N J et al. *BMJ (Clinical research ed.)* vol. 305,6868 (1992): 1534-6." With permission from BMJ Publishing Group Ltd[78]

Imitating the success of hemiarthroplasty in the Smith-Peterson hip, in the 1940s, Campbell attempted a metallic moulded hemiarthroplasty of the femoral condyle, designed to articulate with the native tibial plateau. A stemmed version, the Massachusetts General Hospital Femoral Condylar Replacement, was dogged by loosening. In the 1950s, MacIntosh then McKeever introduced interposition components designed to resurface the tibial plateau, articulating directly with the native femoral condyle. Early MacIntosh acrylic designs were later replaced by metal blocks (Figure 2.12). Despite early pain relief, the lack of fixation led to migration, subsidence and dislocation.

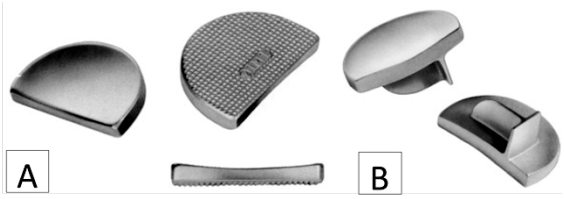


Figure 2.12. The MacIntosh (A) and McKeever (B) Tibial Plateau Interposition Arthroplasties

Reproduced from "UHMWPE Biomaterials Handbook, Chapter 7 The Origins and Adaptations of UHMWPE for Knee Replacements" Steven M. Kurtz. Pages 81-95. Copyright (2009) with permission from Elsevier. CCC[79].

By early 1950, the Shiers[80], then later the Walldius Hinge (Figure 2.13) gained popularity, initially manufactured in acrylic, then later in Vitallium alloy (65% cobalt, 30% chrome, 5% molybdenum)[81], with intramedullary press-fit stems and a roller hinge at the joint line, held in place with a locking bolt. Early gait analysis suggested an improvement, with up to 37% of subjects walking without aids following surgery, compared to 17% pre-operatively ($p<0.05$)[82]. However, ultimately, along with its successor, the GUEPAR hinge, the implant's inability to replicate physiological rotation resulted in shear stresses, early loosening and/or periprosthetic fracture.

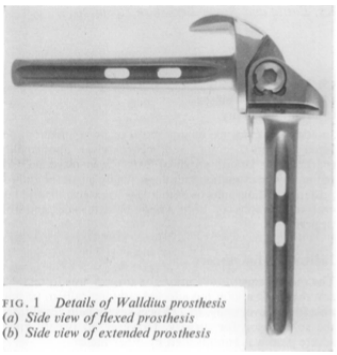

FIG. 1 *Details of Walldius prosthesis*
(a) Side view of flexed prosthesis
(b) Side view of extended prosthesis

Figure 2.13. The Wallidus Hinged Prosthesis

Reproduced from "Wallidus arthroplasty of the knee. Follow-up study of 51 operations" J M Moll, P J Chermerman, R I Meanock, F M Andrews, Annals of the Rheumatic Diseases. Vol 32, Pages 397 – 405. Copyright Notice 2021, with permission from BMJ Publishing Group Ltd [82]

The introduction of Ultra-High-Molecular-Weight Polyethylene (UHMWPE) in 1963 and polymethyl-methacrylate (PMMA) cement in 1971 led to significant advances in arthroplasty technology. Reduction of shear stress and improved fixation meant that long intramedullary stems became redundant in the primary setting. The following two decades paved the way for modern arthroplasty with TKA development occurring throughout Europe, North America and Japan.

The Gunston knee (1960, Figure 2.14) was the first cemented knee replacement. Here, a "runner" made of stainless steel was cemented into the distal femur, articulating within the "track" of a high

density polyethylene platform cemented into the tibial plateau[83]. It's bi-unicondylar design simultaneously resurfaced the medial and lateral tibiofemoral joints, leaving the native patellofemoral joint and cruciate ligaments intact.

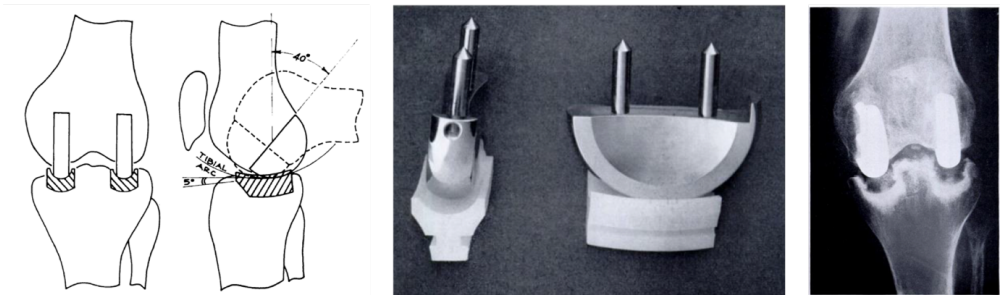


Figure 2.14. The Gunston Knee – a bi-unicondylar resurfacing arthroplasty

Reproduced with permission under license CCC from The Journal of Bone & Joint Surgery (Br)[83]

Gunston published the two and a half year outcomes of 22 cases, reporting significant and lasting pain relief without loss (or improvement) of range of movement. Improved stability was reported in 13 cases[83]. Gunston's post-operative assessment of the patients bears remarkable resemblance to today's Patient Reported Outcome Measures (PROMs), though it was not formally reported as a 'score', rather each outcome was reported on its own merit. Patients could expect to remain in hospital for up to eight weeks post-operation[83]. Used predominantly in Rheumatoid Arthritis patients, progressive inflammatory arthropathy resulted in poor survivorship.

John Charnley, a colleague of Gunston, introduced the 'Load Angle Inlay' bi-condylar arthroplasty, utilising convex polyethylene femoral components which articulated with flat tibial trays (Figure 2.15). The implant suffered catastrophic failures related to loosening.



Figure 2.15. Charnley's Load Angle Inlay Knee Replacement

Reproduced from "A comparison of isokinetic strength testing and gait analysis in patients with posterior cruciate-retaining and substituting knee arthroplasties" Colizzza et al. Under 'CCC' from Elsevier[84]

By 1970, allegedly through an error in manufacturing, the Marmor Modular Knee system (Figure 2.16) had introduced the concept of resurfacing the femoral condyle with metal components rather than polyethylene. Again, a bi-unicondylar design, the metal femoral component articulated with an all-polyethylene tibial tray[85].

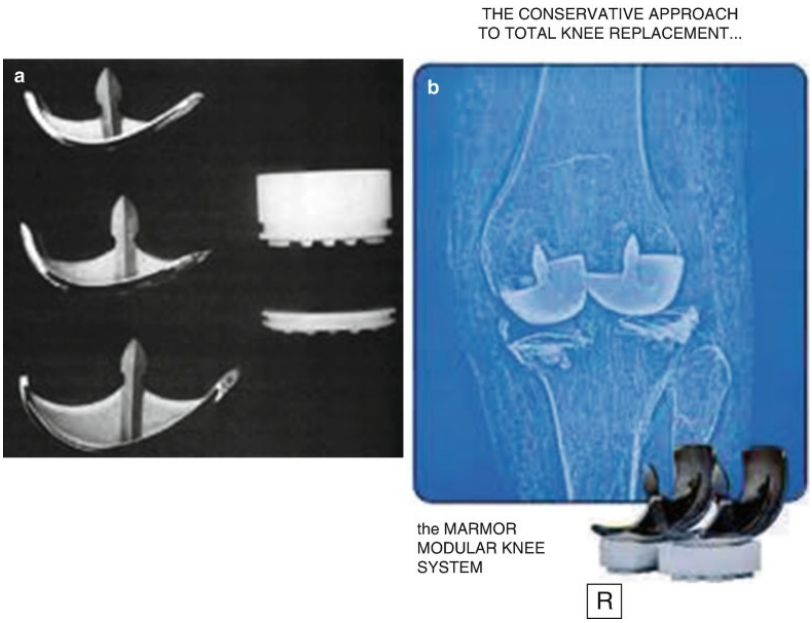


Figure 2.16. The Marmor Modular Knee System

Reprinted by permission from Springer Nature "History of the Unicompartmental Knee Arthroplasty" by Saisal Akram, Brett Levine, COPYRIGHT 2019. CCC[86]

The concept of a multi-radius metallic femoral component articulating on a flat polyethylene surface lived on, with the evolution of multiple 'fixed' bearing designs. Early examples included the Lotus Knee and the Cartier Knee, with the latter using a metal-backed polyethylene, designed (with varying degrees of success) to "grip" the tibial plateau.

At this juncture, knee replacement designs diverged into total or partial knee replacement.

2.6.1 Anatomic TKAs

TKA design rationales broadly followed two philosophies – anatomic and functional. Anatomic designs attempted to incorporate the rationale of Charnley's and Marmor's bi-unicondylar replacements, but reduce variability through the introduction of bone and cruciate ligament sparing 'linked' femoral prostheses. Technically demanding procedures required skilled and careful surgery. All-polyethylene tibial components would articulate with metallic femoral components, with low

articular conformity. Early examples included Townley's Anatomic Total Knee; the Geomedic and later the Geometric knee; the Duocondylar Knee developed by Peter Walker, John Insall and Chitranjan Ranawat (Figure 2.17); the Kodama-Yamamoto knee and the Leeds Knee.

The anatomic designs relied heavily on native kinematics, typically utilising a horse-shoed shaped tibial component, or, in the case of the Duocondylar, two polyethylene tibial components, preserving the central tibial eminence and the ACL (Figure 2.17)[87, 88]. The linked femoral resurfacings aimed to preserve the cruciates but reduce the number of variables associated with surgical technique and implant orientation common to the Gunston and Charnley knees. Anatomic TKAs benefited from early success, but in the longer-term failed due to tibial loosening, subsidence and fatigue failure of the interconnecting bars (Figure 2.18)[87, 89]. Under or over-correction of deformity, instability and subsequent development of PFJ symptoms were also reported[87].

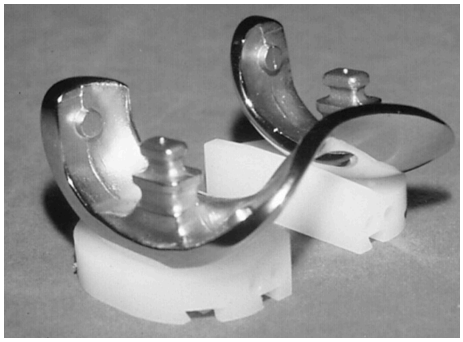


Figure 2.17. The Duocondylar Prosthesis

Reproduced from "The Insall Legacy in Total Knee Arthroplasty", Giles Scuderi, W. Scott and Gregory Tchejeyan. Clinical Orthopaedics and Related Research. CCC Nov 2001. With permission from Wolters Kluwer Health, Inc.[90]

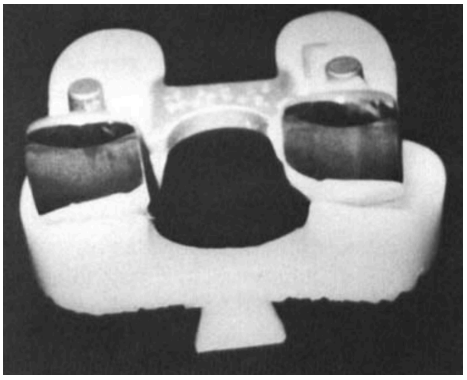


Figure 2.18. Geometric Knee showing plastic deformation of the tibial component

Reproduced from "Roentgenographic Evaluation of Geometric Total Knee Arthroplasty with a Six-Year Average Follow-up Period" Taehiko Torisu and Hideho Morita. Clinical Orthopaedics and Related Research. CCC Nov 2001. With permission from Wolters Kluwer Health, Inc.[91]

2.6.2 Functional TKAs

Whilst anatomic TKA relied on native anatomy to control kinematics, functional TKA designs looked to replicate and reproduce native function through design features of the implants themselves. Functional TKAs were highly congruent and distributed the load evenly across the components, typically necessitating bi-cruciate resection. An early example was the Freeman-Swanson knee, first implanted in 1970, later adapted to the Imperial College / London Hospital (ICLH) knee, 1976. The Freeman-Swanson and the ICLH knees were 'roller in trough' designs which allowed flexion and extension, but at the expense of rotation or medial-lateral stability[89] (Figure 2.19). The ICLH featured an extended anterior flange to improve patella tracking and reduce pain, which had been problematic with the Freeman-Swanson knee[86]. The volume of bone and soft-tissue resection required for the ICLH knee was considerable.

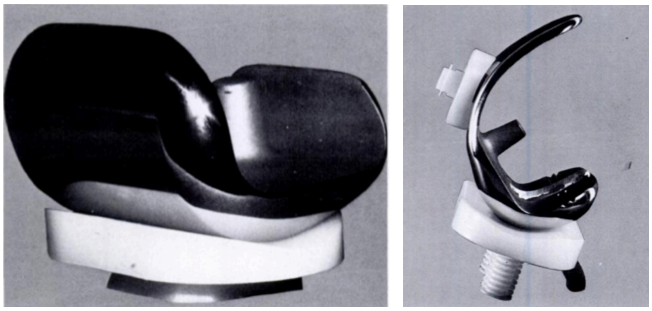


Figure 2.19. The Freeman-Swanson Knee (Left) and the ICLH Knee (Right)

Reproduced from "The Freeman-Swanson ICLH total knee arthroplasty" Goldbery, V M; Henderson, B T. The Journey of Bone & Joint Surgery. CCC Dec 1980 Volume 62, p 1338 - 1344. With permission from Wolters Kluwer Health, Inc.[86]

By the early 1970s, Freeman, Swanson and others had devised a series of basic principles that remain largely relevant to modern arthroplasty. Freeman suggested that, for successful arthroplasty[92]:

1) Bone cuts should:
    a. Be as minimal as feasible, leaving enough for arthrodesis should the procedure fail
    b. Leave large flat surfaces of cancellous bone at the implant interface
2) Implants should:
    a. Be of minimal constraint, so as to reduce the shear stresses at the implant-bone interface and avoid loosening.
    b. Create a low-friction environment
    c. Facilitate a range of motion of -5 to 90° flexion
    d. Avoid hyperextension, but through gradual actions, rather than sudden.
    e. Spread the load over the largest possible interface
    f. Control rotation and prevent excessive movement in any direction
    g. Avoid point-loading, material wear or creep, which may lead to wear debris. Where wear-debris in unavoidable, it should be innocuous.
    h. Be affordable: offering as few size options as is feasible.
    i. Not require mandatory patella resurfacing
3) Procedures should:
    a. Follow a standard, reproducible technique
    b. Minimise periprosthetic joint infection
        i. Reduce anatomical dead spaces
        ii. Use short intramedullary alignment rods
        iii. Avoid intramedullary cementing
4) Soft tissues should:
    a. Provide restraint, specifically the collateral ligaments
    b. Not be relied upon for anterior-posterior stability. It is assumed that the diseased knee includes poor-functioning cruciate ligaments

Further advances in the Functional TKA philosophy evolved from the 'Total Condylar Prosthesis', which comprised a metallic femoral component with symmetrical medial and lateral condyles, which evenly distributed load across a congruent articulation with a polyethylene monoblock tibia. A moulded central cam was designed to reduce anterior-posterior mid-flexion instability as a

consequence of cruciate ligament resection. The importance of stability and the evolution of the central cam-and-post became a significant design rationale for the first Insall-Burstein Total Condylar Knee, which stabilised the knee and made the contact point more posterior, facilitating deeper flexion. However, to accommodate the cam-and-post, a significant amount of bone resection was required from the distal femur. The principles of the Total Condylar Prosthesis and the Duocondylar Anatomic knee merged, eventually leading to the PFC Sigma (De Puy), introduced in 1984, and later the Attune® knee system (De Puy Figure 2.20) which have a posterior-cruciate retaining and posterior-stabilised; cemented and cementless options.

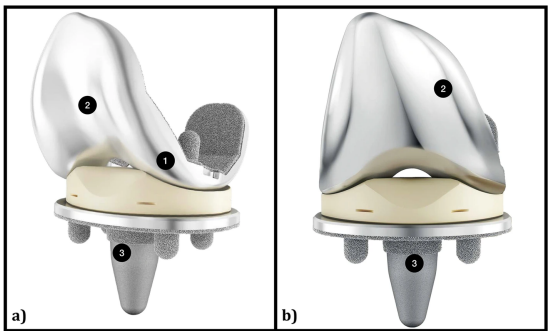


Figure 2.20. The Attune Total Knee Prosthesis

Shown here as a posterior-cruciate retaining cementless device. Reproduced with permission from "Design and rationale of the ATtune Knee Outcome Study (ATKOS): multicentre prospective evaluation of a novel uncemented rotating platform knee system." Rachid Rassir Maarten V. Rademakers et al. Springer Nature under open access Creative Commons CC BY license[93]

In part, inspired John O'Connor's UKA mobile bearing, discussed in more detail in the next section, the Beuchel-Pappas knee and the Low Contact Stress (LCS) functional TKA systems introduced the concept of mobile meniscal-bearings and rotating platform designs. It had been reported that increasing surface congruity during peak loading activity, such as walking or running, permitted tolerable bearing contact stresses, while unconstrained rotation reduced shear stress and avoided loosening[94]. The Vanguard Knee (Zimmer-Biomet, Warsaw, USA) is an example of a more recent mobile-bearing TKA system.

2.6.3 Medial-Pivot TKA systems

Whilst the ICLH knee relied on simplified knee movements, refinements led to a medial-pivot philosophy (Figure 2.21): First generation designs included the Medial Rotation Knee™ (MRK™, MatOrtho®) and its descendent, the SAIPH® bi-cruciate sacrificing designs featuring an asymmetrical highly congruent polyethylene bearing with a deep-dish on the medial side. It's said that this allows medial ball-in-socket type rotation whilst preventing significant medial anterior-posterior translation and mid-flexion instability[95-99].

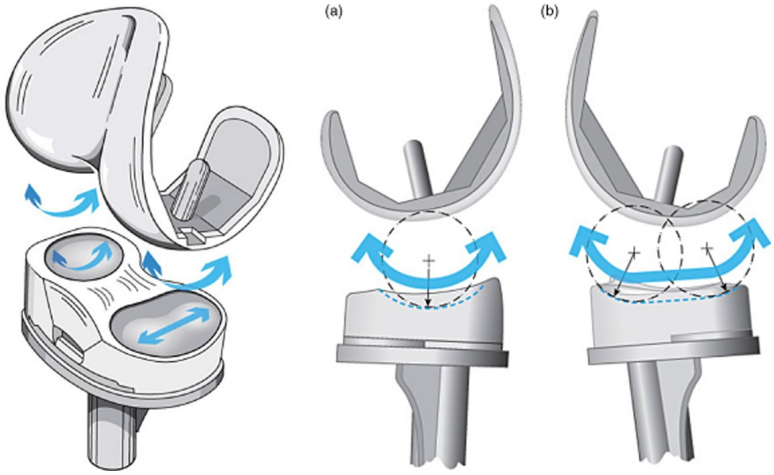


Figure 2.21. The Medial Pivot Knee Implant

Design, featuring a highly congruent medial ball and socket and a lateral sliding surface. Reproduced with permission from Midterm results using a medial pivot total knee replacement compared with the Australian National Joint Replacement Registry data" Justus−Martijn Brinkman, Preet Singh Bubra, Peter Walker, et al. ANZ Journal of Surgery. CCC from John Wiley and Sons[100]

2.6.4 Bi-Cruciate Retaining TKA Systems

As arthroplasty patients have become younger, more active and with greater expectations, efforts have been made to overcome abnormal kinematics and mid-flexion instability by preserving the ACL and PCL through the use of horseshoe shaped tibial components[101-103]. Two bi-cruciate retaining TKA (BCR TKA) devices have evolved: the Journey™ II XR (Smith & Nephew, Memphis, TN, USA. Figure 2.22) is a contemporary descendant of the Leeds Knee, which includes asymmetrical tibial polyethylene fixed bearing, as does the Vanguard™ XP (Zimmer Biomet, Warsaw, USA, Figure 2.23).

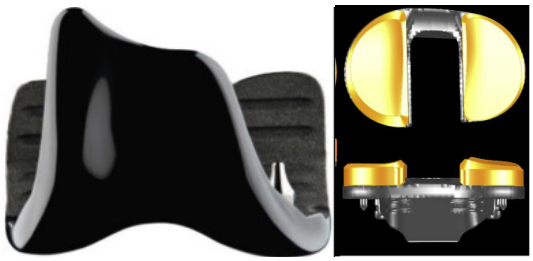


Figure 2.22. Femoral (Left) and Tibial (Right) Components of the Journey™ II XR (Smith & Nephew)

Reprinted from "In Vivo Knee Kinematics: How Important Are the Roles of Femoral Geometry and the Cruciate Ligaments?", Lauren A Smith et al. Journal of Arthroplasty 1445-1454, CCC. Copyright (2021), with permission from Elsevier[104]



Figure 2.23 Vanguard™ XP (Zimmer Biomet, Warsaw, IN, USA)

Reprinted by permission from Springer Nature: Bicruciate-Retaining TKA: How to Achieve Near-Normal Kinematics. Rob Middleton, Andrew Price. Copyright Jan 2017.CCC[105]

BCR TKAs are designed to permit femoral roll-back, reduce lateral compartment restraint and preserve nearer-normal kinematics during treadmill walking, stair stepping and maximum flexion activities[103]. Small studies have reported that BCR TKA designs are associated with faster return to nearer-normal gait with greater top walking speeds and increased stride length at 6 weeks post-surgery, compared to the Bi-Cruciate Stabilised designs, though by 3 months the gap appears to close[106]. Others have reported that BCR TKA are preferred by patients, compared to posterior-stabilised TKA[107, 108], comparable to UKA in terms of the Forgotten Joint Score[109, 110]. However, many of these studies are not randomised and the range of reported outcomes is wide.

Restoration and preservation of kinematics with BCR TKA devices are controversial. Some report improved function and survivorship, especially with the introduction of an asymmetrical convex inlay in the lateral compartment [111-113]. Others suggest significant variability in pivot patterns; an incomplete "screw home" mechanism[110] and failure to restore native tibiofemoral articular contact

kinematics[114]. Despite being more anterior-posterior stable, independent centres report that BCR TKA does not restore symmetrical knee motion during gait[115]. BCR TKA appears to have higher than expected revision rates with early failures[116], reportedly due to tibial loosening, ACL impingement and pain[117]. A large RCT, the 'All Ligaments Left Inside Knee Arthroplasty Trial' (ALLIKAT) was recently suspended due to high failure rates. First-generation devices have reported that at 22 years following surgery, up to 38% have limited range of motion, and increased pain compared to standard implants[118, 119]. Intra-articular fibroproliferative arthrofibrotic nodules known as Cyclops lesions have been reported, which result in impingent and an extension block in the femoral notch[120]. The surgical technique is more demanding than standard TKA, and the learning curve has an impact on revision rates[117]. As with their predecessors, the linkage bar on the tibial component has been associated with high rates of intra-operative tibial eminence avulsion, necessitating conversion to posterior-cruciate retaining designs, and stiffness in deep flexion[116].

2.7 Partial Knee Replacement

Whilst TKA designs became more invasive, simultaneous attempts were being made to specifically replace or resurface only worn areas of the joint, preserving healthy native tissues. Early indications for PKA were for Rheumatoid Arthritis, which often led to premature failure due to progressive inflammatory arthropathy. Inflammatory arthropathy is now considered, by many, a contraindication to PKA. Up to 75% of patients have macroscopic OA confined to the medial compartment[121, 122] which, in the presence of a functional ACL, is typically anteromedial (AMOA) on the tibial plateau[4, 123]. Subjects demonstrate strong peak adduction moments, altered frontal plane alignment and ground reaction forces when walking [124-127]. A consequence of AMOA, even Kellgren-Lawrence grade IV, is that any intra-articular varus deformity may be corrected passively in extension[128], as the femur articulates with intact, full-thickness posteromedial cartilage, preserving the length of the medial collateral ligament and preventing the need for ligament releases necessitated by TKA[129]. Movement of the UKA is unconstrained and subject to ligamentous control.

UKA devices may broadly be categorised into fixed bearing and mobile bearing designs. The St Georg 'Sled' (Link GmbH, Hamburg, Germany) was introduced soon after the Marmor knee, and features a polyradial metal femoral component, which articulates with a flat all-polyethylene tibial component. The polyradial femoral component is typical of fixed-bearing UKA designs, said to restore native femoral condyle geometry. Articulation with a flat tibial component reduces constraint, but is associated with early wear and premature failure, along with bone-implant interface loosening as a consequence of high shear stresses[76, 130, 131]. Design modifications include the 'Journey' Uni knee (Smith & Nephew, Memphis, TN), a descendent of the Marmor knee but with the introduction of ultrahigh-molecular-weight polyethylene and the option of an oxidized zirconium coating, said to increase hardness, reduce scratching and protect against nickel allergy[132, 133]. The Persona® Partial Knee (Zimmer Biomet, Warsaw), based on the Zimmer Miller Galante Uni, has introduced the concept of Vitamin E enriched polyethylene, said to prevent oxidation *in vitro*, thereby strengthening the polyethylene and reducing wear, though the evidence is limited[134-136].

In 1966, Oxford Professor John O'Connor, a lecturer of Engineering Science and Orthopaedic Surgeon and academic Mr John Goodfellow founded a working partnership that, together with the outstanding work of Nigel Shrive, an Oxford DPhil student, would prove pivotal in the evolution of PKA. Together, they invented and developed the Oxford® Unicondylar Knee Replacement (OUKR). The OUKR uses a spherical femoral component and a flat tibial base plate, which articulates with a

fully-congruent mobile meniscal bearing capable of distributing load across a wide contact area. The shape of the device allows unrestricted distraction, sliding and rolling movements, without applying shear stresses at the implant-bone interface, a known cause of aseptic loosening. The flat underside of the meniscal bearing slides on the highly polished tibial baseplate, held in place by balanced soft-tissue tension alone, a concept which with the passage of time, created a low-wear environment of the polyethylene – a major downfall of its predecessors. The baseplate itself sinks a keel into the tibial plateau, for rotational stability.

Goodfellow's first case series of 300 Oxford Knees were in the Bi-UKA form, with excellent outcomes. Goodfellow and O'Connor's original device, later to become known as the Phase 1 (Figure 2.24), was first implanted into a human subject in 1976, in a Bi-unicondylar form. With time, it was recognised that in knees with functional ACLs, AMOA predominated. By 1982, the OUKR was being implanted as a medial unicondylar device. The femoral and tibial components were made of cobalt chromium molybdenum alloy.

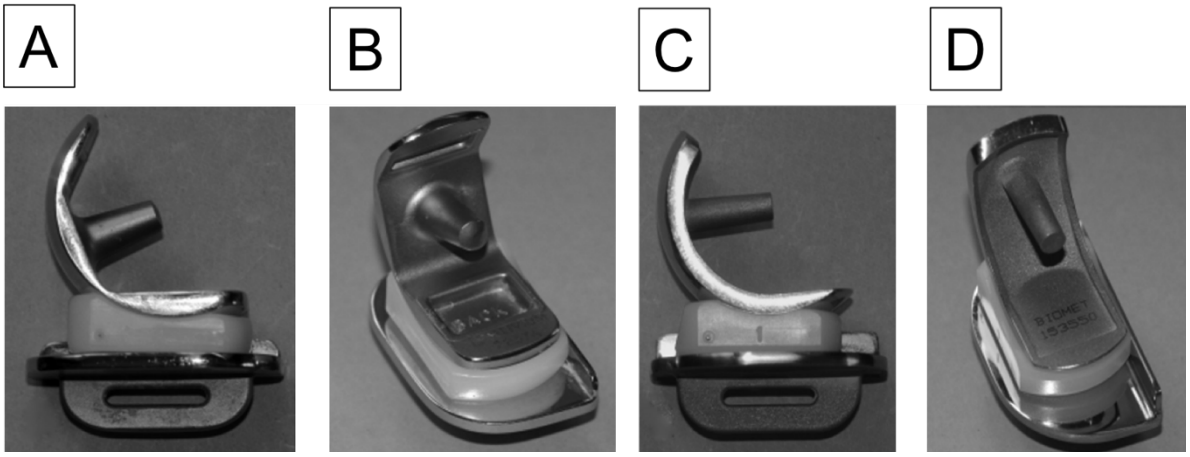


Figure 2.24. Phase 1 Oxford® Partial Knee (Biomet, UK)

Lateral (A) and Posterior-medial (B) views, and Phase 2 Oxford® Partial Knee: Lateral (A) and Posterior-medial (B) views demonstrating the change in interior geometry as a result of the introduction of a femoral milling tool. Reproduced from "Polyethylene wear of mobile-bearing unicompartmental knee replacement at 20 years" B.J.L Kendrick et al. Vol 93-B. With permission from The Bone & Joint Journal. April 2011. Copyright CCC[137].

The device and instrumentation have been modified several times since its conception. In 1987 the Phase 2 device altered the internal geometry of the original design, introducing a milling tool for contouring the femur, enabling the extension gap to be increased in 1mm increments, to balance the flexion gap. The 1998 Phase 3 OUKR featured a twin peg femoral component, designed to resist

rotational torque. In 2004, a cementless options for the Oxford® Partial Knee was introduced as an alternative to cemented components, inducing bone grown onto Porous Plasma Spray® and hydroxyapatite backed prostheses (Figure 2.25). Multiple studies suggest improved fixation relative to cemented Oxford, with shorter operative time and comparable or superior clinical outcomes at 5 years post-operation[138, 139]. The instrumentation was overhauled in 2011 with the introduction of Microplasty®, designed to establish an accurate position for the tibial cut based on the long-axis of the femoral condyle and the depth of the existing flexion gap.

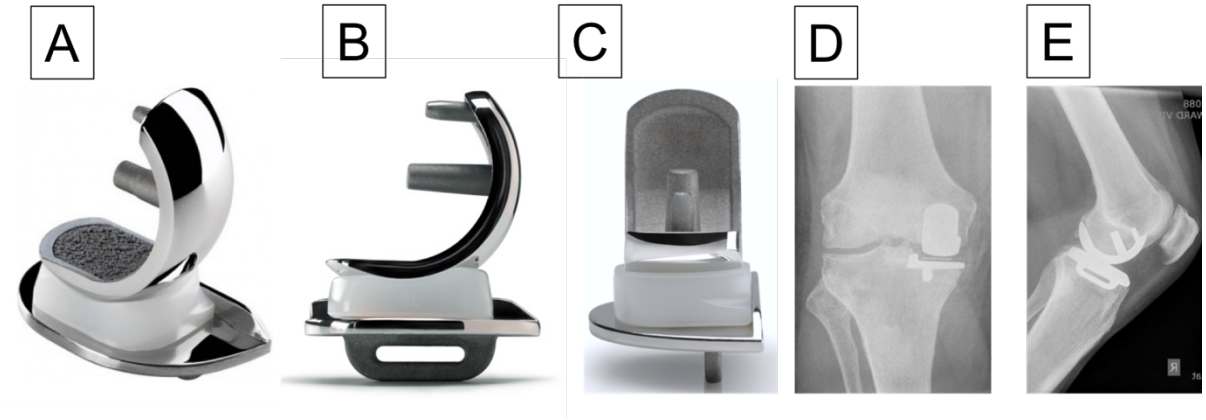


Figure 2.25. Oxford® Medial Unicompartmental Knee Replacement (ZimmerBiomet™)

Anteromedial view, cementless in the flexed position (A), Lateral view in the flexed position (B) and Posterior view, cemented, in the flexed position (C) demonstrating a single radius femoral component and fully-congruent mobile meniscal bearing. Implant pictures reprinted from "Mobile-bearing Unicondylar Knee Arthroplasty. The Oxford Experience" , Hurst, J.M and Berend, K.R. Orthopaedic clinics of North America, Copyright 2015 Pages 113-124, with permission from Elsevier[140]. Anterior-Posterior (D) and Lateral (E) Radiographs with Oxford® Medial Unicompartmental Knee Replacement in situ. Radiographs used with permission.

Today, the Oxford® OUKR (Figure 2.25) is the market leader in partial knee replacement. The 28th Annual Report from the NJR included 141,094 UKAs, of which 75,317 (53%) were OUKR designs (of four different iterations)[76]. The remainder of UKAs in current use are, predominantly, fixed bearing designs.

2.7.1 The Lateral Tibiofemoral Joint

Progression of lateral compartment OA in patients with anteromedial arthrosis (AMOA) is very rare in the absence of surgical intervention[141, 142] but is often cited as the mode of failure and requirement for revision after both UKA-M and UKA-L[143, 144]. Long-term follow-up studies have not

always supported this[145]. At 11 years following UKA-M, Weale et al. from the Oxford group, reported no deterioration in the radiographic appearances of the lateral compartment, suggesting that AMOA is a focal disorder which does not progress after successful UKA-M[146]. Multiple studies from the Oxford Group and the National Joint Registry, using data from 15-20-year follow-up studies, place the revision rate between 2.3 – 2.6% [147-149].

In the native flexed knee, the tight medial collateral ligament prevents opening of the medial compartment by more than 2mm, however, the slack lateral collateral ligament can result in opening of the lateral compartment by up to 7mm[150]. The original flat mobile bearing lateral Oxford UKA had a 5-year survival rate of just 82%, largely the result of 10% incidence of dislocation, in part due to unconstrained lateral laxity[151]. The design was modified to a domed prosthesis with a biconcave bearing, articulating on a concave tibial base plate. Further modifications to surgical technique were recommended: the lateral para-patella approach was introduced; the tibial component was internally rotated and surgeons were advised against 'over-stuffing' and over-milling the femur which can elevate the joint line and increase the dislocation rate. These changes reduced the dislocation rate to 1.7% in the designers' hands[152, 153]. Despite this, independent studies reported more mixed findings: one series of 50 knees reported a 6% dislocation rate with the domed design (Figure 2.26)[154] whilst our own group reported 64 knees with no dislocations[155].

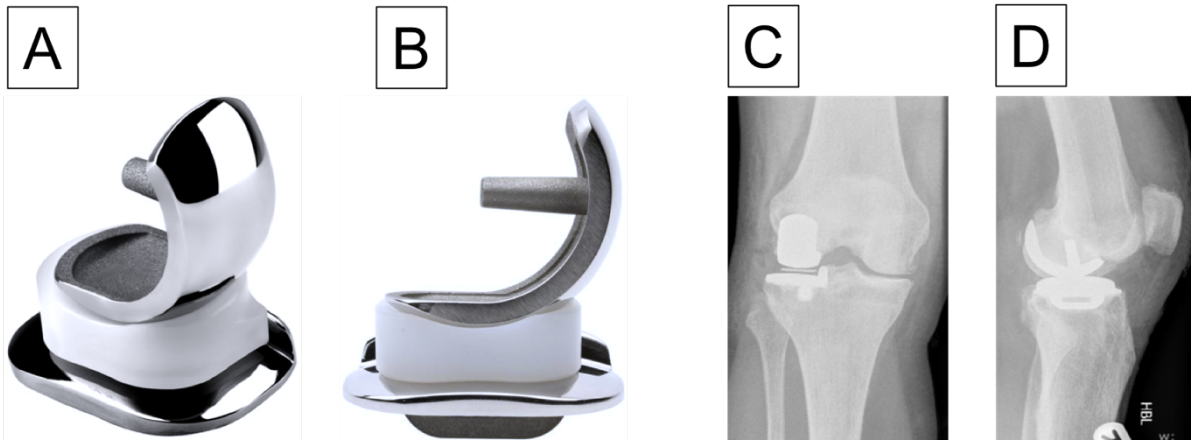


Figure 2.26.Oxford® Cemented Domed Lateral Unicompartmental Knee Replacement (ZimmerBiomet™)

Anterolateral[156] (A) and Lateral View (B) of implant demonstrating fully congruent mobile meniscal bearing on a domed tibial tray. Images with kind permission of Zimmer Biomet (all rights reserved by Zimmer Biomet). Anterior-posterior (C) and Lateral (D) Radiographs of right knee with Oxford® Domed Lateral in situ. Radiographs used with permission.

The ‘Fixed Lateral Oxford®’ (Zimmer Biomet, Figure 2.27) avoids the possibility of bearing dislocation. Its monoblock design commits the surgeon to the bearing height at the point of implantation of the tibial tray and the entire tibial component must be revised in the event of bearing wear. The femoral component of the Fixed Lateral Oxford is identical to that of the medial OUKR. The tibial monoblock is cemented. The advantages and disadvantages of fixed Vs. mobile bearings in UKA-L continue to be debated[157]. Femoral roll-back creates shear stress on the lateral tibial component, which may result in loosening of fixed bearing devices and is a disadvantage[158]. The mobile bearing device resists these shear stresses, but at the expense of higher revision rates for recurrent dislocation, often regarded as a failure of the arthroplasty. Forster et al. reported no significant difference in the OKS, the clinical and functional American knee society score or range of motion between fixed and mobile bearing UKA-L, but noted three revisions in the mobile bearing group for loosening, and one intra-operative tibial fracture during implantation of the fixed bearing device[158].

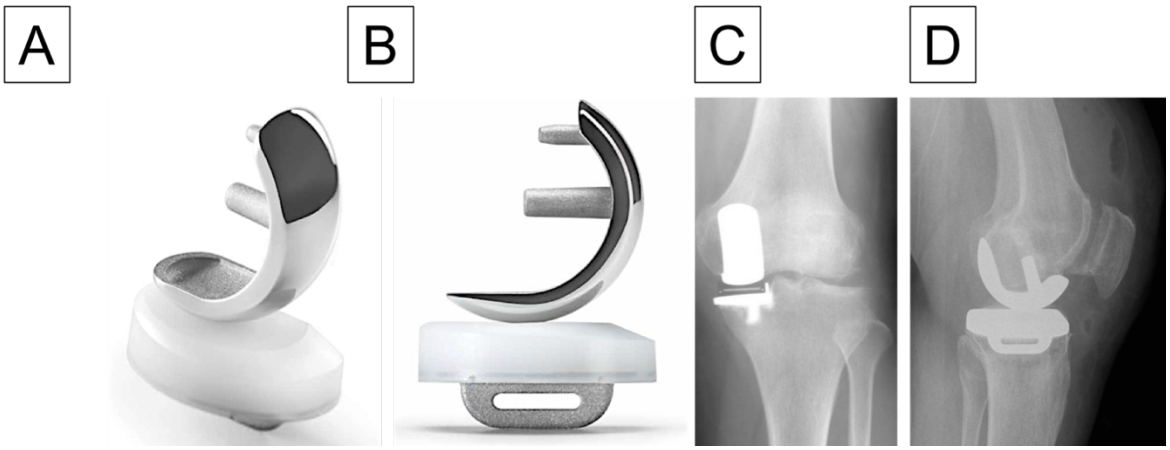


Figure 2.27. Oxford® Cemented Fixed Lateral Unicompartmental Knee Replacement (ZimmerBiomet™)

Anterolateral view, cemented in the flexed position (A), Lateral view in the flexed position (B). Implant pictures reprinted from “Minimally invasive lateral unicompartmental knee replacement: Early results from an independent centre using the Oxford fixed lateral prosthesis” Walker et al. The Knee, Jan 2020[159] Copyright 2020, with permission from Elsevier (D) Anterior-Posterior (C) and Lateral (E) Radiographs. Radiographs used with permission.

2.8 Patellofemoral Arthroplasty

The Patellofemoral compartment is the second most commonly affected by OA and is often associated with medial OA[160]. Isolated patellofemoral OA is rare, reported to be in the region of 2% of males and 8% of females [72, 161]. The treatment of isolated PFJ OA remains controversial. The PFJ may be replaced in isolation through a patellofemoral arthroplasty (PFA), whereby the selectively resurfaced trochlear groove articulates with a patellar button. However, just 1.2% of primary knee replacements in the NJR are PFAs[76], with low uptake thought to be a consequence of high revision rates, 25.36% (95% CI: 23.94 – 26.85) at 15 years, compared to 4.09% (95% CI: 3.94 – 4.19) for unconstrained fixed bearing cemented TKAs[76]. For this reason, the mainstay of surgical treatment for isolated PFJ OA remains TKA, but with the inevitable sacrifice of the tibiofemoral joints and the ACL. Whilst TKA has been used with reasonable success for treatment of isolated patellofemoral OA, anterior knee pain can continue in over 19% of patients[162, 163]. Those that do undergo PFA are typically 12 years younger than those undergoing TKA (median age 58 years, IQR 50-67) and predominantly female (77.4%)[76].

The first PFA designs were proposed by MacKeever in 1955[164] and by Cartier in the 1970s (Smith-Nephew-Richards)[165]. Despite promising early results, excessive wear led to early failure. The complex kinematics of the PFJ make isolated replacement difficult: limited constraint helps replicate the degrees of freedom of the native patellar, but risks subluxation and dislocation, whilst too much constraint risks increased contact pressures and untimely polyethylene wear. Two basic principles may be employed to address the trochlea: inlay and onlay. First generation PFA predominantly focused on inlay designs: specific resurfacing of the worn articular cartilage by embedding the prosthesis within the subchondral bone leaving the articulation flush with the remaining native joint, re-creating native anatomy (Figure 2.28). Despite promising early results, many first-generation devices failed as a consequence of recurrent patellar subluxation or dislocation, thought to be a consequence of failure to correct native mis-alignment and mal-tracking, that may have contributed toward the primary PFJ OA.

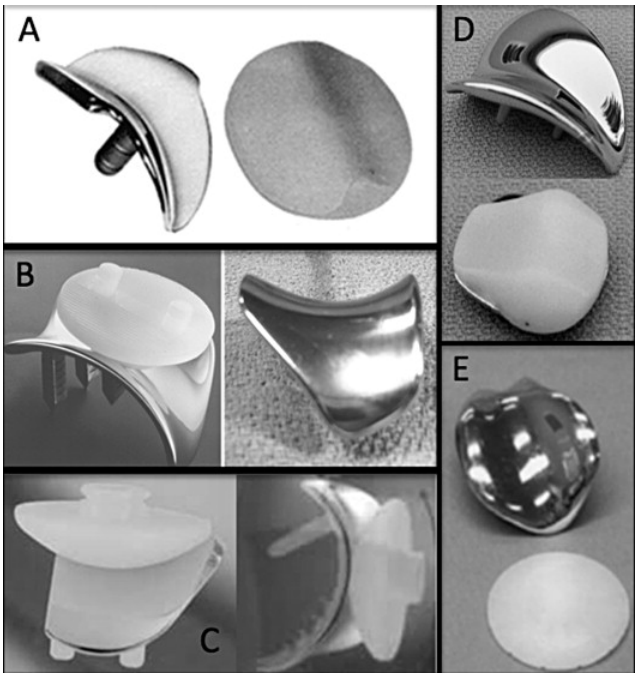


Figure 2.28. First generation inlay patellofemoral arthroplasty devices: A) Richards III™ B) Spherocentric™, C) Autocentric™ D) LCS™ E) Lubinus™

Reproduced from Lustig "Patellofemoral Arthroplasty" Orthop Traumatol Surg Res. 2014 Feb;100(1 Suppl):S35-43.Copyright 2014 with permission from Elsevier[166]

Second generation PFA favoured onlay designs (Figure 2.29, Figure 2.30), essentially utilising the same anterior-resection as a corresponding TKA, to completely replace the anterior compartment. Valgus alignment of the trochlear component seeks to align the device with the mechanical axis of the limb, in an attempt to correct any native mal-tracking, whilst internal rotation of the component is associated with higher re-operation rates[167].

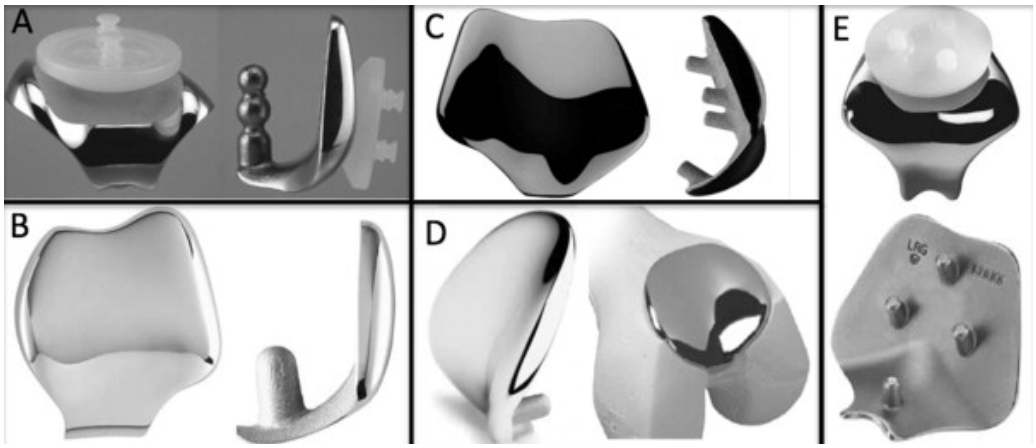


Figure 2.29. Onlay patellofemoral arthroplasty designs. A) Hermes™, B) Vanguard™, C) Journey Competitor™, D) Gender Solutions™, E) Avon™

Reproduced from Lustig "Patellofemoral Arthroplasty" Orthop Traumatol Surg Res. 2014 Feb;100(1 Suppl):S35-43.Copyright 2014 with permission from Elsevier[166]

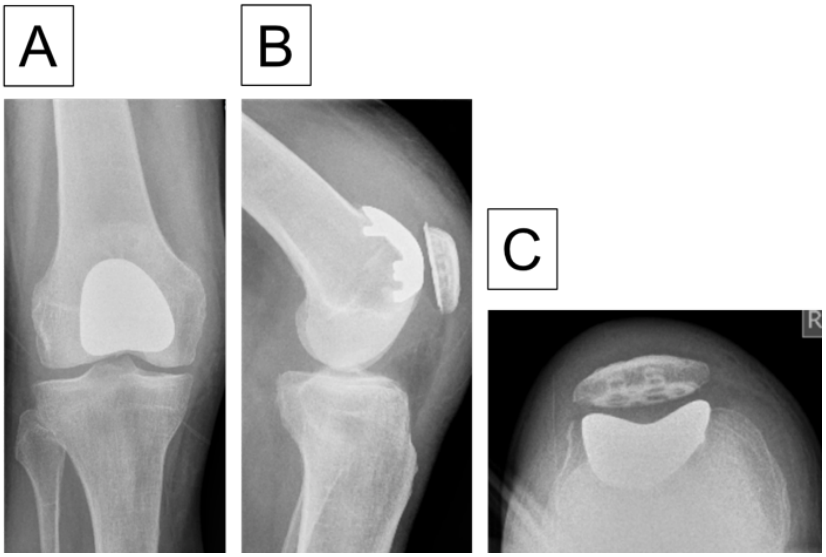


Figure 2.30 Gender™ Solutions (ZimmerBiomet™) Patellofemoral Arthroplasty

A) Anterior-posterior view (B), Lateral (C) Skyline Radiographs used with permission.

The shape of the button itself may also vary, with some implants utilising a domed design, whilst other, 'anatomic' designs are asymmetric, to imitate the facets of the native trochlea.

2.8.1 Failure of patellofemoral arthroplasty

Common reasons for revision of PFA include patellar maltracking, instability or recurrent subluxation, persistent anterior knee pain, progressive arthritis in the tibiofemoral joint, and loosening.

Contemporary trochlear designs use a number of design modifications to address maltracking and instability, these include an extended anterior flange, to ensure contact with the patellar button even in full extension, an elevated lateral flange, to resist the lateral pull of quadriceps which may contribute toward patellar subluxation; an extended distal flange, which prevents articulation of the patellar button on the native femoral condyle, and altered depths of the trochlear groove, which change the level of constraint of the implant. These design modifications have important implications with regards to space and geometry when used in combination with UKA, which will be discussed in the next section[166].

Anterior knee pain may arise for a number of issues. Inadequate soft-tissue releases, over-sized implants or insufficient bony resection can result in 'over-stuffing', stretching the extensor mechanism, increasing contact pressures and reducing function[168, 169]. Residual patella alta may contribute toward post-operative instability[170].

Progressive arthritis is the most common reason for revision of PFA, and may be up to 22% after 5-15 years[171, 172]. Some studies have shown this to be independent of the functional outcomes achieved by primary PFA[168] but may be associated with the indication for primary PFA, with those operated on for primary OA more likely to be revised for progression (17% revision rate at 7 years), relative to those operated on for trochlear dysplasia (0% revision rate)[173].

2.9 The Rationale for Alternatives to Total Knee Arthroplasty

When faced with the choice between PKA and TKA, patients, surgeons and commissioners must first understand the arguments for and against each procedure in terms of safety, efficacy and health economics.

2.9.1 Patient Safety, Peri-operative Risk, Morbidity and Mortality

Patient safety is paramount. Much work has been undertaken to investigate this in relation to PKA and TKA. In 2014, Liddle et al. undertook a propensity matched cohort study of 101,432 knees in patients undergoing UKA (medial and lateral, n=25,358), Vs TKA (n=76,074)[174]. The study investigated perioperative adverse events, morbidity, mortality and re-operation rates. Linked National Joint Registry (NJR) and Hospital Episodes Statistics (HES) data were used to determine re-operation rates of UKA and TKA over an eight-year period following surgery, and used NJR and PROMs linked data to compare patient reported outcomes where data were available. Liddle et al. reported that the risk to the patient of TKA was considerably higher compared to the relative risk of UKA-M[174]. Specifically, the risk of death in the first 30 post-operative days was four times higher for TKA than for matched UKA-M subjects, and 15% more likely during the eight years following surgery (hazard ratio 30 days 0.23, 90 days 0.45, eight years 0.87). The latter is, perhaps, a surrogate marker of divergent overall health following the alternate procedures. Primary TKA is associated with significantly higher cumulative mortality than PKA at all time points in the NJR (Table 2.2) although these figures were not adjusted for selection, so there is residual confounding (Hunt et al 2018)[76].

Liddle et al. reported the risk of requiring a blood transfusion was four times higher following TKA, the risk of stroke three times higher, and the risk of venous thromboembolism, myocardial infarction or deep infection requiring further surgery, were twice as likely following TKA, compared to UKA-M[174]. Mean length of stay following UKA was 1.4 days shorter following UKA, with a much-reduced re-admission rate within the first year[174]. Other studies drew similar conclusions, reporting that PKA has the advantage of reduced morbidity and mortality; less disruption of the soft-tissue envelope; reduced risk of periprosthetic fracture by greatly reduced stress shielding; shorter recovery times; and limited blood loss compared to TKA[147, 174-178].

Procedure	2021 NJR Report (N=)	Number of Deaths	Cumulative Mortality (95% confidence intervals) according to time since primary surgery					
			30 Days	90 days	1 Year	5 Years	10 Years	15 Years
TKA	1,184,306	226,710 (19.1%)	0.16 (0.15 – 0.17)	0.30 (0.29 – 0.31)	1.03 (1.01 – 10.5)	8.71 (8.65 – 8.77)	26.08 (25.96 – 26.19)	48.11 (47.89 – 48.33)
UKA	121,986	12,895 (10.6 %)	0.03 (0.03 – 0.05)	0.08 (0.06 – 0.09)	0.39 (0.36 – 0.43)	4.16 (4.04 – 4.30)	13.31 (13.04 – 13.60)	27.45 (26.85 – 28.07)
PFA	14,852		0.04 (0.02 – 0.09)	0.13 (0.08 – 0.20)	0.38 (0.29 – 0.49)	3.71 (3.39 – 4.06)	11.67 (10.99 – 12.39)	23.37 (21.80 – 25.02)
CPKA	561		0	0	0.36 (0.09 – 1.43)	2.57 (1.50 – 4.39)	7.88 (5.53 – 11.17)	25.94 (11.44 – 52.40)

Table 2.2. Cumulative mortality according to primary arthroplasty type.

Summarised from the National Joint Registry 2021 Report. CPKA in blue as <250 cases at risk[76].

Procedure	2021 NJR (N=)	Median Age (IQR) years	Sex (% F)	Cumulative Revision Rates (95% confidence interval)			
				5 years	10 Years	15 years	17 years
Cemented TKA	781,402	70 (64 – 76)	57.6	1.92 (1.89 – 1.96)	2.91 (2.86 – 2.96)	4.09 (3.99 – 4.19)	4.49 (4.33 – 4.64)
Cemented UKA	96,187	64 (57 – 71)	46.7	5.62 (5.46 – 5.78)	10.41 (10.16 – 10.66)	15.74 (5.28 – 16.22)	17.59 (16.85 – 18.36)
Uncemented / Hybrid UKA	29,268	65 (58 – 72)	45.0	3.89 (3.63 – 4.18)	7.61 (6.95 – 8.32)	11.52 (9.88 – 13.42)*	No Data
PFA	15,639	58 (50 – 67)	77.4	9.42 (8.93 – 9.94)	18.23 (17.45 – 19.05)	25.36 (23.94 0 26.85)	26.71 (24.86 – 28.66)*
CPKA	586	60 (53 – 67)		9.84 (7.60 – 12.69)	14.02 (11.07 – 17.67)*	No Data	No Data

Table 2.3. Data from the National Joint Registry 2021 according to arthroplasty type.

Total Knee Arthroplasty (TKA), Unicompartmental arthroplasty (UKA), Patellofemoral Arthroplasty (PFA) and Primary Combined Partial Knee Arthroplasty (CPKA) * indicates fewer than 250 cases remained at risk of revision at these time points and are therefore less reliable[76]

2.9.2 Survivorship and Revision Rates

Implant longevity and survivorship is a quantifiable, commonly used marker of success or failure of procedures and implants. As such, survivorship is the cornerstone of comparisons drawn between procedures and implants in all major joint registries across the world. Joint registries collect and analyse data from all arthroplasty procedures and as such, provide 'big data' from which differences between procedures, implants, hospitals and individual surgeons can be calculated, and any areas of concern identified and rectified.

TKA are associated with relatively low revision rates, 4.49% at 17 years in the UK National Joint Registry (NJR, Table 2.3)[76], whereas PKA continues to be associated with significantly higher revision rates, compared to TKA, double or more at all time points in the 2021 NJR report[76]. At 10 years, revision rates of cemented UKA (medial or lateral) are 3.2 times higher than TKA. By 17 years, the rate has increased to 3.6 times higher (Table 2.3)[76]. Cementless UKA has been associated with increased survival, but revision rates at 10 years remain 2.4 times higher than for cemented TKA[76]. Liddle et al. reported that in the eight-years following surgery, 40% more UKA subjects than TKA subjects go on to further surgery, whilst the relative risk of revision surgery following UKA is twice that of TKA (Hazard Ratio 1.37, 95% CI 1.31 – 1.44)[174].

In June 2018, the NJR modified its K1 (primary) and K2 (revision) data collection forms, completed by all surgical teams following any knee replacement procedure[179]. The updated format allows, for the first time, respondents to differentiate between medial and lateral UKA, where previously they had been analysed as a single procedure, and to indicate where multiple PKA devices have been implanted during a single primary procedure (K1) or that the primary PKA had been retained and additional PKA had been implanted to newly degenerate compartment(s) (K2). The latter is now referred to as the 'Compartmental Approach' to revision of PKA. In its 2020 report, the NJR introduce the multicompartment concept, but reporting was limited due to low numbers[180]. In the 2021 NJR report, a total of just 586 primary 'multicompartmental' cases were recorded (<0.1% of primary procedures), with no indication of implant combination[76].

PFA and compartmental arthroplasty have the highest recorded revision rates, 5.6 times higher than TKA at 10 years (Table 2.3), though the numbers of compartmental arthroplasty procedures recorded in the NJR are very small[76]. With this in mind, early data from CPKA in the NJR suggests a revision rate comparable to PFA at 5 years, 1.8 times higher than for cemented UKA, 2.5 times

higher for cementless UKA, and 4.5 times higher than for cemented TKA[76]. According to the NJR, progressive arthritis remains the most common cause for revision of all PKA subgroups (UKA-M, UKA-L, PFA and CPKA), regardless of bearing type or cementation. For UKA, the second most common cause for revision is aseptic loosening / lysis, then pain, for PFA and CPKA, after progressive arthritis, pain is the second most common reason for revision[76].

2.9.3 Limitations of Joint Registries

Survivorship is a blunt tool. An implant is deemed to have 'failed' should any further arthroplasty be performed in the joint. For example, a UKA may be considered 'revised' regardless of whether it has undergone exchange of meniscal bearing for wear, leaving the metallic components in place or whether it has been revised to a complex TKA with augments and metaphyseal stems, to compensate for bone loss on removal of the implant. Equally, it is regarded a failure, even if left in situ and a second PKA implanted to a newly degenerate native compartment. This is discussed in more detail in Chapter 4. Similarly, a TKA may be considered 'revised' following secondary patellar resurfacing, or equally, when revised to stemmed implants, requiring metaphyseal augmentation, and/or additional constraint, which are commonly required[174]. In its current form, the NJR report does not distinguish between such procedures, all are deemed to have 'failed' and count equally towards the survivorship data, which so many rely upon as an indicator of success or failure, though clearly the magnitude of these second procedures has significant implications for the patient[180, 181]. The NJR does not collect data on unrevised implants that have poor function or are persistently painful, nor does it register amputation or death resulting from knee surgery. Therefore, these procedures are all considered a 'success' in registry terms[182].

Ease of revision procedures has a marked impact on willingness to perform second surgery. In a study based on New Zealand Joint Registry (NZJR) data, Goodfellow et al. demonstrated that there are significant differences in thresholds for revision of UKA relative to TKA[182]. Specifically, when comparing UKA and TKA patients with very poor outcomes (OKS < 20 points), 12% of TKA patients underwent revision surgery, compared to 63% of UKA patients. Across all OKS scores, UKA revision rates were six-times that of TKA, even though more UKA patients reported 'good' or 'excellent' outcomes[182]. Goodfellow concluded that the increased revision rates were independent of patient reported outcome, and not because of poor results, but more likely a consequence of lower thresholds for revision of UKA in part, because the procedure is much easier to perform and generally associated with good outcomes[182, 183]. Conversely, the risk of revision of primary TKA when

performed in young, active patients is significant and outcomes often unsatisfactory. In a recent study by Sabah et al. of 10,727 patients undergoing revision of primary TKA, only 53% achieved a measurable improvement in both post-revision joint function and improved health-related quality of life, with the fewest gains seen in patients under 60 years, and those with relatively high pre-revision OKS[184]. One quarter of patients felt that revision TKA surgery did not resolve their knee problem, leaving them dissatisfied, while 46% reported at least one complication, ten-times higher than those undergoing primary TKA. Baker et al. reported that, after revision surgery, 17% of patients reported 'no improvement' in OKS[185], while in another study, 47% reported experiencing severe to unbearable chronic pain; reduced walking distances and the need for a walking aid[186].

Surgeon-level data has great advantages. Designed to identify surgeons with high revision rates, registries provide surgeons with information on their performance, relative to others in the registry. The NJR's outlier system uses funnel plots based on case load against the number of expected revisions. Surgeons with a revision rate more than three standard deviations from the mean are identified as outliers and encouraged to rectify their practise. However, since UKA has a higher revision rate than TKA, surgeons who perform more UKAs typically have higher revision rates, and therefore are at greater risk of being identified outliers. This has led to significantly fewer surgeons performing UKA and, for those that persist, some have cautiously narrowed their indications leading to smaller case numbers, which may be associated with increased complication rates[183]. Murray et al. have reported that surgeons should aim for 20-40% of their caseload to be UKA, to minimise complication rates resulting from inexperience, and maximise benefits to patients[183].

2.9.4 Functional Outcomes

PKA preserves bone stock in the unaffected compartments; retains functional cruciate ligaments and closer replicates the kinematics and biomechanics of the native knee[187-189]. Given the relatively infrequent occurrence of tricompartmental TKA with a dysfunctional ACL, removal of healthy peri-articular tissue and functional cruciate ligaments in TKA is common, and often to the detriment of post-operative function[64], whereas the tissue-sparing nature of PKA contributes towards the restoration of more normal kinematics[190]. Quadriceps strength is often deficient in patients with end-stage OA, and is addressed in more detail in Chapter 5. However, in brief, OA patients typically walk slowly compared to disease-free subjects, with a measurable impact of quadriceps deficiency[191]. This functional impairment can persist following TKA if quadriceps strength is not addressed adequately before and after surgery[84, 192-195]. By comparison, PKA are associated with

higher post-operative activity-levels[196]. PKA knees are said to retain more normal proprioception[197] whereas Nobel et al. reported that, compared to age- and gender-matched subjects, up to 52% of TKA patients continue to experience substantial limitation in function, particularly when undertaking activities associated with high biomechanical demand[198].

2.9.5 Patient Reported Outcomes

Patient Reported Outcomes Measures (PROMs) are tools that have been used since the 1990s to capture subjective reports of function, patient satisfaction and quality of life at multiple time points before and after surgery and are discussed in more detail in Chapter 7. Typically survey based, these validated measures offer patients the opportunity to self-score, without the influence or pressure of their treating clinician[199]. Several scoring systems exist, each with their own advantages and disadvantages. In the UK, the Oxford Knee Score (OKS) and the Euro-Qol 5D (EQ-5D) five level scores are some of the most widely used and validated, with a strong research base. The OKS is an knee arthroplasty specific metric which utilises 12 questions which carry a maximum score of four each, to produce a score out of 48[200]. The EQ-5D is a quality-of-life metric which consists of five domains : mobility, self-care, usual activities, pain/discomfort and anxiety/depression. The EQ-5D assessed general quality of life, carries a maximum score of 1, indicating 'full health' and a minimum score of -0.594, where 0 is 'death' and negative scores indicating a state worse than death, reported by up to 12% of those waiting for knee arthroplasty surgery[201].

Discrete scores are extremely useful in quantifying subjective outcomes, enabling comparisons, linear scales, variability over time and, in very large numbers, the comparison of different procedures with subgroup analysis of different patient cohorts according to patient demographics, functional demands and expectations. PROMs support commissioners and health care providers when justifying expensive interventions. Disadvantages include a failure to account for the impact of age or comorbidities beyond the knee joint[202-206]. Reported ceiling or floor effects suggest the inability to discriminate between subjects scoring the very best or worst possible scores[207, 208]. This becomes particularly relevant when trying to discriminate between implants or procedures which result in very high functional outcomes, in young active patients, for example.

The interplay between post-operative function and patient reported outcomes and the fulfilment of patient expectation is complex and multifactorial. Post-operative dissatisfaction is not necessarily a consequence of poor function. Individuals with poor pre-operative function are more likely to have

poor post-operative function[209], but these individuals may be highly satisfied[205], in part due to lower pre-operative expectations[210]. Following surgery, the most important predictor of satisfaction is the relief of pain, which is typically met[210, 211] . Patients often place emphasis on and expect to ascend and descend the stairs without difficulty, kneel, squat and rise unaided from a chair, and those who fail to achieve this following surgery often report higher levels of dissatisfaction[210].

TKA is a well-established procedure with a proven track record, and a large body of evidence to suggest it is successful[212]. TKA associated with marked improvements in health-related quality of life[213, 214] and patient reported outcomes[215-218]. Following surgery, 66% report excellent pain relief [219], 98% of working-age people return to work, with no gender differences noted[220]. However, dissatisfaction rates of up to 30% following TKA are widely reported[221, 222]. The recent meta-analysis by Shan et al. reviewed 19 studies, reporting that overall quality of life, pain and function improved with TKA, but up to 25% of patients report dissatisfaction, in some studies up to 11.7 years following surgery[223-225]. Bourne et al. studied 1803 primary TKA subjects, finding that one in five were dissatisfied[221], whilst others report that one in five patients would not elect to undergo TKA again[226]. Only 37-56% remain very active, able to perform regular physical activity[224, 226] and 24% reported the requirement of walking aids or the presence of a limp[223, 224]. 15% of patients were no linger living independently at home following surgery[224]. Others have suggested that only 44% participate in desired activity levels following recovery[227, 228] and just 52% return to normal daily activities[219].

Liddle et al. undertook a study of 15,000 patients comparing pre-operative and post-operative PROMS of UKA and TKA[229]. Matched patients reported higher mean post-operative OKS following UKA (UKA 38 Vs TKA 36) and a higher proportion of UKA patients reported excellent scores >41 points (odds ration 1.6). The same were true of EQ-5D, with statistically significant advantages in pain, mobility, function and self-care. Statistical difference in PROMs does not necessarily relate to a clinical difference. This has been quantified by a minimal clinically important difference (MCID): a clinically meaningful qualitative difference in outcome associated with a quantitative score[230, 231]. The MCID for OKS is estimated as a mean difference of 5 points[232]. The predicted MCID of EQ-5D 5L is widely debated, but Coretti et al. estimated it to be between 0.03 – 0.54[233].

The recent 'Total Or Partial Knee Arthroplasty Trial' (TOPKAT) analysed outcomes for 528 patients, randomised to receive either PKA (UKA-M) or TKA. All patients had isolated bone on bone medial OA and were considered eligible for either procedure. The study was conducted across 27 sites, with 68 surgeons performing the procedures in expertise equipoise. At 5 years, data were available for 464

patients (PKA n=233, TKA n=231). Overall satisfaction rate for PKA were higher: the mean OKS for medial UKA were 38.9±10.1 compared to TKA 37±10.6, though this did not reach statistical significance (mean difference 1·04, 95% CI −0·42 to 2·50; p=0·159)[234]. Differences in EQ-5D five dimensions, three levels were PKA 0.744 ±0.29 Vs TKA 0.717 ± 0.32 (mean difference 0.018, 95% CI -0.33 to 0.069, p=0.48). Advantages of PKA in the EQ-5D visual analogue scale were marked (p = 0.004 in favour of better outcomes for PKA). Specifically, PKA patients reported a feeling of the knee being better after surgery (PKA 95% Vs TKA 90%, p-0.016) and a willingness to undergo surgery again (PKA 91% Vs TKA 84%)[234].

TOPKAT reported TKA to have more post-operative complications specifically with regards to stiffness and pain. In contrast to the NJR, re-operation and revision rates were statistically similar: higher than anticipated for TKA, based on registry predictions, and lower than anticipated for UKA-M. This is an important and much debated finding, likely the product of the experience of those surgeons performing PKA: all needed to have PKA experience prior to joining the study, whereas registry data inevitably captures a learning curve and the outcomes of less experienced PKA surgeons. This reinforces the need to more robust training in successful PKA techniques amongst aspiring knee surgeons. Revision rates amongst trial patients are thought to be subject to higher thresholds for consideration of second surgery, in part due to more intensive follow-up and investigation of “unexplained pain” which may commonly result in revision to TKA in routine practice.

TOPKAT also reported a number of second operations that are not captured by the NJR, for example manipulation under anaesthetic procedures for stiffness, were significantly higher amongst the TKA cohort. PKA had a shorter length of stay (mean 3.2 days Vs 4.3 days, p<0.0001); was more cost-effective (0.240 additional quality-adjusted life-years) and £910 less expensive. In the years since TOPKAT began, there have been significant advances in same-day discharge following PKA with some reporting mean same calendar-day discharge rates of up to 92%, which has not been replicated in TKA[235]. The financial implications of this are substantial. Beard et al.[234] concluded from TOPKAT that PKA (UKA-M) should be offered as the first line of treatment for those with advanced isolated medial compartment OA on the basis of similar outcomes, high levels of satisfaction and a willingness to undergo the surgery again, with equivalent revision rates to TKA in experienced hands. TOPKAT 10 year outcomes are awaited.

3 Combined Partial Knee Arthroplasty

Whilst the benefits of PKA are well established, their use is limited when the extent of OA extends beyond a single compartment. In these individuals, TKA remains the most common treatment, even if the ACL and third compartment are intact[76]. At the advent of PKA, the original Bi-UKA design were in widespread use. Their use declined as AMOA were recognised as the primary pattern of wear and emerging TKA technologies appeared a suitable alternative for more widespread disease, before evidence of their limitations emerged. There has been a recent resurgence in interest in Combined Partial Knee Arthroplasty (CPKA), the compartmental approach to treatment of OA. The use of multiple PKAs used together within the same knee seemingly have the advantage of preserving both cruciate ligaments, healthy peri-articular tissues and the intact third compartment.

Broadly speaking, four combinations of CPKA exist (Figure 3.1): Bi-Compartmental Arthroplasty (BCA): A PFA in combination with either a medial (BCA-M) or lateral (BCA-L) UKA; Bi-Unicondylar Arthroplasty: Medial and Lateral UKA (Bi-UKA); and Tri-Compartmental: medial and lateral UKA with PFA (TCA) The evolution of this classification and acronyms is discussed in more detail in Chapter 4. Of those with end-stage OA, it has been reported that 50% have single compartment OA (27% medial, 18% PFJ, 5% lateral), 33% have two-compartment OA (23% medial/PFJ, 5% lateral/PFJ and 5% medial/lateral), whilst tricompartmental OA is the least common pattern, present in 17% (7.4 – 22.2%)[4]. For those with two-compartment disease, CPKA offers a bone, ACL and meniscal sparing alternative to TKA, but relatively little is known of their biomechanics or clinical outcomes.

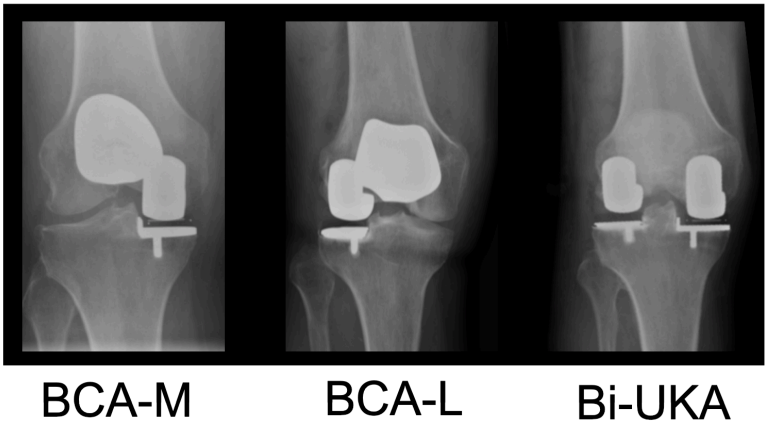


Figure 3.1. Combined Partial Knee Arthroplasty.

Anterior-Posterior Radiographs reproduced with permission Left to Right: Medial Bicompartmental Arthroplasty (BCA-M), Lateral Bicompartmental Arthroplasty (BCA-L): and Bi-Unicondylar Arthroplasty (Bi-UKA).

3.1 The Compartmental Approach

Primary CPKA may be undertaken as a single-stage procedure in the presence of two-compartment OA at presentation. However, following PKA for single compartment OA, native compartment progression of arthritis remains a challenge to treat (Figure 3.2)[76]. This is discussed in more detail in chapter 4, but in brief, the most likely procedure is to remove the existing PKA, and replace the entire joint with a TKA, most often a 'primary' TKA implant[76] but bone loss can necessitate metaphyseal augmentation, stems or additional constraint. Often, the PKA in situ is functioning normally, but its removal is mandated to address the degenerate compartment with a TKA. An alternative it to add a second PKA to the degenerate compartment, leaving the primary in situ (Figure 3.3). This 'compartmental approach to revision of PKA' has been suggested to represent a "second primary" procedure, likely retaining the benefits of primary PKA, specifically with regards to low peri-operative risk, short hospital stays and early return to function[236]. Relative to revision to TKA, this would be a significantly more conservative, safer, undertaking[237], but there is little evidence on subsequent degeneration of the third compartment, ligament disruption; the impact on the primary PKA in terms of change in alignment; altered wear; modified shear stresses or loosening.



Figure 3.2. Pre-revision radiographs of bilateral knees demonstrating native medial compartment wear with a spared patellofemoral joint, ten years following lateral unicompartmental arthroplasty

Radiographs reproduced with permission

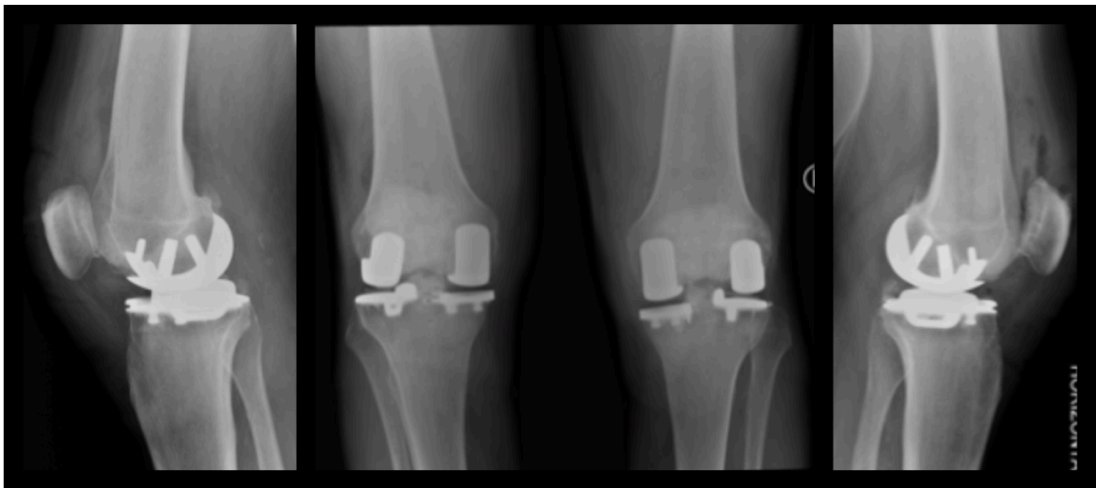


Figure 3.3. Post-revision radiographs of staged Bi-Unicondylar Arthroplasty (Bi-UKA) following the simultaneous addition of bilateral medial unicompartmental arthroplasty implants

Radiographs reproduced with permission

The function and satisfaction of the staged compartmental approach are relatively unknown. Potential advantages include the retention of healthy tissue and the ACL, faster recovery times and the avoidance of TKA, with its associated functional limitations. However, there is limited information regarding the biomechanics, functional outcomes or patient satisfaction associated with this approach, all of which are explored in this thesis. Disadvantages include the need for second surgery, with its associated impact on the physical and emotional wellbeing of the patient, which advocates of primary TKA state are avoided if the entire joint is replaced in the first procedure; potential wound issues if the original incision is re-used and slower recovery than the initial surgery due to residual stiffness or aggravation of previously healed tissues.

3.2 Medial Bicompartmental Arthroplasty

OA of the knee is typically a non-uniform phenomenon, most commonly affecting the medial compartment[4, 72, 74]. Some studies report the radiographic incidence of bi-compartmental OA to be as high as 58% [74]. Tricompartmental OA is the least common pattern. Structural changes in the cartilage of the knee have been reported, in radiographic and cadaveric studies, to progress to the patellofemoral compartment from the medial compartment[238 239]. Cartilage loss in the lateral compartment is least common[4]. An Oxford study of 793 patients (824 knees) undergoing UKA-M reported trochlear full-thickness cartilage loss in 13% of subjects: 9% medial facet, 4% lateral facet[240, 241], but other studies have placed the incidence of PFJ OA to be higher: one in three subjects

over 60 years have been reported to have OA visible on radiographs, providing skyline views are taken, since the sensitivity for PFJ OA on lateral views may be as low as 66%[242]. Arno et al. reported that of 97 subjects undergoing TKA with a varus deformity, 61% (n=59) had a healthy lateral compartment on visual and histological analysis[243]. Of their 97 subjects, they concluded that jut 21% would have been eligible for UKA-M, with 28% (n=17) excluded due to concurrent medial tibiofemoral and PFJ OA in the presence of functional cruciate ligaments. These subjects would be candidates for BCA-M, yet all underwent TKA[243].

The importance of patellofemoral disease to outcomes of UKA-M is widely debated. Kozin and Scott indicated that PFJ OA should be considered a contraindication to UKA[244, 245]. However, Goodfellow and O'Connor reported the presence of patellofemoral OA made no difference to the outcome of 125 UKA[187]. Their conclusions were later supported by further evidence from the Oxford group, leading to the advice that medial facet PFJ OA could be safely ignored[240, 241, 246, 247]. During a study of 824 knees selected to undergo medial OUKR, full-thickness patellofemoral cartilage loss was found in 13% of trochleae, 9% of medial patella facets and 4% of lateral patella facets[240]. OA of the trochlea and medial patellar facet appeared to make no difference to the functional outcome of a UKA and was not, therefore, deemed a contraindication to UKA. In other series, progression of patellofemoral OA or patellofemoral impingement has been reported as a primary cause of failure of fixed bearing UKAs[248 249]. Munk et al. reported that patients undergoing UKA-M in the presence of lateral patella subluxation have a higher incidence of flexion contracture and varus deformity, exacerbating PFJ symptoms, resulting in inferior outcomes[250]. The majority of surgeons elect to perform a TKA in these patients[251, 252], the inevitable consequence is resection of healthy lateral bone, menisci, and a functional ACL.

Severe lateral facet PFJ OA, however, has very different implications for the outcomes of UKA and to many, remains a contraindication to PKA[240, 241, 251, 252]. Similarly, concerns over concurrent or progressive tibiofemoral wear in the presence of isolated end-stage PFJ OA, likely contribute to the very low implantation rates of PFA[189]. Nicol et al. reported that in a series of 103 consecutive PFAs, progression of symptomatic tibiofemoral OA had necessitated revision of 12% of cases, with mean time to revision just 55 months (range 14 – 95 months)[173]. Of the surviving PFAs, 7% of knees were reported to show radiographic evidence of medial compartment OA progression by 51 months following surgery, whereas no knees showed lateral compartment OA. PFA performed in absence of pre-operative trochlear dysplasia was reported as a risk factor for progression of tibiofemoral OA [173].

3.3 First Generation Monolithic Bicompartmental Arthroplasty

The femoral component of BCA may be modular (separate UKA and PFA implants used in combination) or monolithic (a single component resurfacing one femoral condyle and the PFJ). The Journey-Deuce (Smith and Nephew, Memphis, TN. Figure 3.4) was an early example of a monolithic BCA-M and much of the early research on BCA-M focused on it.

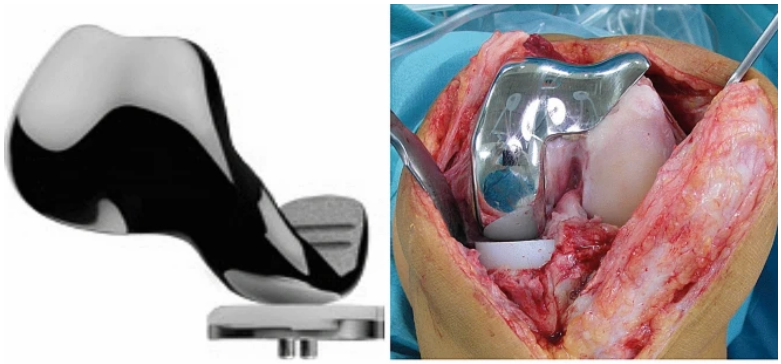


Figure 3.4. Journey-Deuce Medial Bicompartmental Arthroplasty (Smith & Nephew)

Reproduced from "Bicompartmental, medial and patellofemoral knee replacement might be able to maintain unloaded knee kinematics" Yao, D., Akram, I., Daniilidis, K. *et al. Arch Orthop Trauma Surg* (2021). Copyright 2021. CCC with permission from Springer Nature.[253]

3.3.1 Patient Reported Outcomes following Monolithic BCA-M

Morrison et al. reported outcomes following Journey-Deuce BCA-M (n=21) compared to matched TKA subjects (n=33). The Deuce achieved early pain relief and improved range of motion, with high flexion within three months, not seen in TKA until one-year post-surgery. By two years, however, the cohorts had equal outcomes[254]. Palumbo et al. reported on 36 Journey-Deuce knees, with 31% and 17% reporting an excellent or good outcome respectively on the Knee Society Score, meanwhile 39% reported a poor outcome. Subjective outcomes of monolithic BCA-M were poor when compared to historical WOMAC scores for TKA, with persistent pain in 81%, 31% were dissatisfied and 53% reported they would not undergo the surgery again[255].

3.3.2 Functional Outcomes of Monolithic BCA-M

In 2009, Wang et al. compared the kinematics, gait characteristics and extensor moments of the Journey-Deuce (n=8), with the subjects' own unaffected leg, and healthy control subjects (n=10)

reporting that the Deuce demonstrated near-normal frontal plane alignment, kinematics, gait characteristics and similar extensor moments to healthy subjects[256]. Wunschel et. al. used a cadaveric knee model to demonstrate that the ACL-intact Journey-Deuce was anterior-posterior stable in mid-flexion, but destabilised after ACL sacrifice, however it also displayed near-normal internal rotation during early flexion regardless of ACL integrity, in contrast to posterior-cruciate retaining TKAs which demonstrated abnormal external rotation in early flexion[257]. The Journey-Deuce was shown, on lateral radiographs, to replicate more normal lateral compartment roll-back than posterior-cruciate retaining TKA[258]. Leffler et al. reported that the Journey-Deuce was able to replicate the kinematics of the subject's own contralateral non-involved limb and those of a matched group of control subjects when undertaking normal activities of daily living[259].

3.3.3 Survivorship of Monolithic BCA-M

Despite its early promise, in vivo, the Journey-Deuce performed very poorly, blighted by high rates of early revision. Misalignment; sizing difficulties; poor durability; anterior knee pain; limited range of movement and tibial component fractures were all cited as causes for early failure[255]. Particular challenges relate to orientation and sizing of the femoral component and the interplay between alignment to the mechanical axis and orientation for accurate patellar tracking, which do not necessarily correlate to appropriate positioning of the tibial component in all individuals[255, 260, 261]. At times, the prescribed nature of implant alignment fails to accommodate variability of distal femoral morphology and has been shown in some studies to lead to rotational misalignment in up to 20% of cases[170, 255, 262, 263]. An issue resolved, in part, with modular BCA[8, 264].

A number of studies reported different patterns of radiolucency around monolithic systems[7, 8, 255], predominantly affecting the tibial baseplate, which Palumbo et al. concluded was due to micromotion as a consequence of strain at the tibial baseplate bone-cement interface which, whilst not necessarily progressive, were thought to lead to pain[255]. In one short-term study, a 12% revision rate was reported, with 25% of patients complaining of anterior knee pain [265]. In another study of 25 Journey-Deuce BCA-M, three were revised – two for fractured tibial trays (Figure 3.5) and one for patellar instability [262]. Early post-operative complications with the Journey-Deuce were reported to be as high as 28.6%, compared to matched TKA cohorts of 6.1% (p=0.045; odds ratio 6.2). Authors concluded that patient selection and surgeon inexperience contributed to these failures, in addition to issues with the device itself[254]. These reports, plus evidence of tibial subsidence contributed to the US Food and Drug Administration's decision to recall the Journey-Deuce prosthesis in 2010.

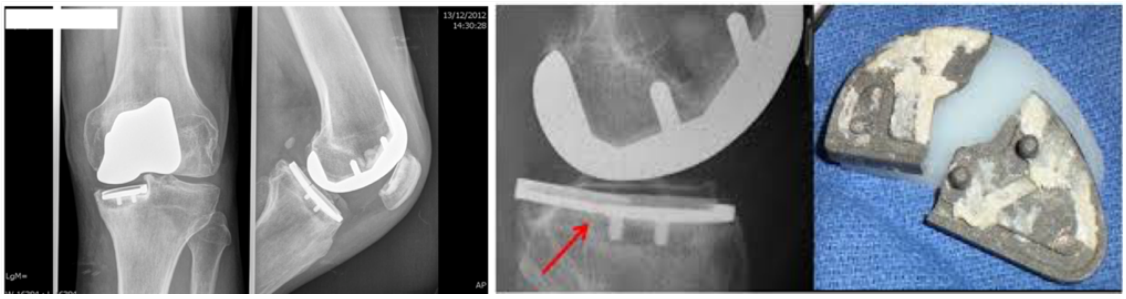


Figure 3.5 Journey-Deuce Tibial Component subsidence and baseplate fracture

Images reproduced from Garner A., Cobb J. (2020) Combined Partial Knee Arthroplasty. In: Rivière C. Vendittoli PA. (eds) Personalized Hip and Knee Joint Replacement. With permission from Springer, Cham. CC-BY-4.0. and from "Initial Experience of the Journey-Deuce Bicompartmental Knee Prosthesis A Review of 36 Cases" Palumbo et al. Journal of Arthroplasty Copyright 2011. With permission from Elsevier. CCC [262, 266]

3.3.4 The future of monolithic BCA-M

Despite the experience from the Journey-Deuce, monolithic designs remain of interest. The iDuo® G2 bicompartmental knee resurfacing system (ConforMIS, Burlington, MA) is a monolithic custom-made BCA-M currently on the market with promising early results in small single-surgeon series[267]. Wang et. al. showed the iDuo to reproduce mechanics, speed and strength comparable to that of the healthy native knee, significantly out-performing TKA[268]. The polyethylene bearing is 2mm thicker than the Journey-Deuce, with a more posterior keel, said to improve stability and reduce the fracture risk. At present, the cost of custom-made implants and 3D printed patient-specific instrumentation in knee surgery remains prohibitive to widespread adoption and, therefore, little is known of the outcomes associated with them, though this may change going forward.

3.4 Modular Compartmental Arthroplasty

Modular CPKA is said to allow the surgeon more freedom to make subtle adjustments according to the distal femoral geometry of the femur, enable more accurate alignment [269], with promising results but a steep learning curve[257, 265, 270-272]. Unlinked components may be implanted accurately according to the orientation and morphology of the specific compartment, hence both patellar tracking and limb alignment can be optimised, independently of each other[273-276]. There is some evidence that BCA is associated with shorter hospital stays; less blood loss; improved scar healing and faster recovery times, compared to TKA[265].

A number of studies have reported excellent outcomes with modular BCA-M in the short- to medium-term[277, 278], although some early modular BCA-M had a 46% incidence of disease progression or radiographic evidence of loosening by 17 years post-operation, likely due to poor quality polyethylene and crude instrumentation necessitating a "free-hand" technique[8]. Aseptic loosening of the PFA implant was the main cause of failure in 20/27 revised BCA-M in one series[8]. Of these, 20 had isolated loosening of the PFA, though 15 implants were cementless. A further 7 failures occurred due to loosening of the tibial component, in some instances related to rapid polyethylene wear[8]. Experience with BCA failure, however, provided much evidence that conversion to TKA was typically straightforward, using primary TKA implants [9, 219, 264, 272]. Bone stock preservation following BCA is particularly significant. The bone removed with BCA is estimated to be between 3.5 – 4 times less than that removed during TKA[279], hence revision to a primary TKA implant is possible in the majority of failed BCA cases[8, 254, 255].

Unlinked BCA-M utilising second and third generation anterior-cut cemented patellofemoral components (Figure 3.6) are associated with improved clinical and biomechanical outcomes[269, 280, 281]. Parratte et al. reported that at mean 12 years follow-up (range 5-23 years) BCA-M was associated with improved flexion, excellent function and high knee society scores[8]. These findings echoed those of Heyse et al. who reported on BCA performed by Cartier, these too showing improved range of motion; favourable WOMAC scores, avoidance of instability symptoms, though a small number of patients reported mild pain on sit-to-stand and difficulty with squatting and kneeling[7].

There is some evidence that BCA perform better in strenuous activities such as independent rising, reciprocal stair climbing and jogging, in part due to restored isokinetic quadriceps function[276, 282]. Excellent early post-operative range of movement and patient satisfaction have been reported after medial and lateral BCA [254, 255, 283]. A nine-year follow-up study of 57 knees (BCA-M n=45, BCA-L n=12) reported high post-operative satisfaction and an overall survival rate of 91.5%, 88.5% for BCA-M and 100% for BCA-L[284]. Two of the five revised BCA-M were for progressive arthritis, with one patient converted to TCA through the addition of a UKA-L.



Figure 3.6. Pre- and Post-operative Radiographs depicting medial tibiofemoral and lateral facet patellofemoral compartment arthrosis treated with an unlinked medial bicompartmental arthroplasty.

Images adapted from Garner A., Cobb J. (2020) Combined Partial Knee Arthroplasty. In: Rivière C. Vendittoli PA. (eds) Personalized Hip and Knee Joint Replacement. With permission from Springer, Cham. CC-BY-4.0

Lonner et al. investigated 12 consecutive BCA-M subjects, implanted with robotic arm assistance, reporting favourable subjective outcomes, and an increase in range of motion from 100° of flexion prior to surgery, to mean 140° of flexion six months post-operation[264]. Meanwhile, Tamam et al. investigated the MAKO robotic-arm (Stryker, USA), reporting favourable outcomes with BCA-M (83%) and BCA-L (17%) at mean 27 months follow up[285]. Patients benefited from significant pain relief and an improvement in the OKS of 18 ± 6 points. Twenty-four patients (83%) reported an excellent outcome. One patient reported a poor functional outcome. No mechanical failures were reported. Kinematic studies of BCA-M have demonstrated advantageous kinematics, stair-climbing and patient satisfaction . Retention of the ACL has been shown in BCA-M to enhance stability, maintain proprioception and nearer normal tibiofemoral kinematics[273]. Compared to TKA, BCA-M are reported to result in a more natural feeling knee[273, 282] with reduced pain and high post-operative patient satisfaction[273].

Others report the differences between BCA and TKA to be minimal and therefore not clinically relevant: Chung and Min measured muscle strength and physical performance in 11 BCAs compared

to 13 TKAs and found them to be similar, with a marginal advantage of TKA during stair ascent, concluding that the performance of BCA does not justify the lower survivorship[283]. Early NJR data suggests revision rates are similar to primary PFA, supported by small cohort series (n=41) where primary PFA and primary BCA-M had 95% survivorship at 5 years.

In summary, there is some evidence that BCA is associated with nearer-normal biomechanics and improved function, which may lead to increased survivorship[7, 8, 286 108, 256, 257, 287]. Two recent systematic reviews and meta-analyses have indicated that, with contemporary implant designs and instrumentation, BCA looks to be a viable alternative to TKA in appropriate patients[288, 289]. BCA may be appropriate for the treatment of bone-on-bone OA in young healthy patients, with high functional demands, but also in elderly, frail patients, who'd likely benefit from faster recovery and reduced peri-operative complications, if indeed that is shown to be the case. However, the evidence for this remains relatively limited compared to those for TKA and single compartment PKA. The studies in this thesis aim to contribute towards this evidence base.

3.5 Bi-Unicondylar Arthroplasty

Early Bi-UKA were performed for severe OA and Rheumatoid Arthritis with some short- to medium-term success but ultimately failed due to progressive inflammatory arthropathy[83, 187]. Modern indications for CPKA are, therefore, now typically limited to OA. Recently, there has been a resurgence in interest in Bi-UKA, in both the primary and staged setting. Medial and lateral compartment OA, in the presence of a functional ACL but absence of lateral facet patellofemoral OA is a relatively rare phenomenon[4, 121], but in these individuals, primary Bi-UKA is an ACL, bone and peri-articular sparing alternative to TKA with evidence that this is both feasible and effective[8, 290, 291].

Goodfellow and O'Connor reported that PCL dysfunction was a contraindication to Bi-UKA, whilst ACL dysfunction strictly-speaking was not[187]. However, they highlighted that ACL integrity does have a major influence on Bi-UKA outcome, with no reported Bi-UKA failures in their series in those with an intact ACL. Romagnoli et al. have described primary Bi-UKA with simultaneous ACL reconstruction[143], but no long-term studies have, to date, reported on outcomes. Goodfellow and O'Connor's other inclusion criteria for primary Bi-UKA included range of motion greater than 75°under general anaesthesia; <40° flexion deformity and <30° varus or valgus deformity[187]. In 2005, Confalonieri et al. described those with bi-unicompartmental OA, greater than 90° of flexion, anterior-posterior stability in the absence of patellofemoral symptoms and varus-valgus deviation of

<10°, as suitable candidates for primary Bi-UKA[9, 292]. The group reported obesity, inflammatory arthropathy, significant patellofemoral symptoms, laxity, flexion contractures <10°, marked varus deformity and obesity to be absolute contraindications to primary Bi-UKA[9, 292].

Advocates of UKA are again considering staged Bi-UKA a bone-sparing, less invasive alternative to revision to TKA, with some evidence of success[293-297]. In their report on staged Bi-UKA, Pandit et al. reported that subjects with native lateral compartment OA, without evidence of loosening of the primary UKA, were suitable candidates, though advised that the surgeon should observe the PFJ and ACL at the time of surgery and proceed to revision of UKA-M to TKA in the presence of significant PFJ OA or ACL insufficiency[293]. Others have highlighted the potential safety benefits of staged Bi-UKA in high-risk patients, considering the procedure to be a "second primary"[296]. There is limited evidence that the risks and benefits are similar to single compartment PKA; that the procedure is less invasive than revision to TKA; that it may result in reduced peri-operative risk and faster return to high function, particularly in younger high-demand patients[296, 298].

3.5.1 Considerations for Bi-UKA surgery

The preferred combinations of mobile and fixed bearing devices remain controversial. Goodfellow and O'Connor highlighted the advantages of mobile-bearing devices in replication of function of the native menisci[187] whilst the majority of reports in the current literature focus on fixed bearing UKA devices [8, 9, 290, 291, 299-301]. Pandit et al. reported success with the addition of a mobile bearing UKA-L to an existing mobile-bearing UKA-M[293], but others highlight mixed outcomes of mobile-bearing UKA-L in isolation, so its use within Bi-UKA is advocated with caution[275, 302, 303]. Others have promoted the use of fixed bearing devices in both compartments, pointing out the potential for increased laxity in the presence of two UKA as a consequence of loss of the secondary stabilisation of the native menisci[296].

Choice of incision is debated in Bi-UKA surgery. For primary Bi-UKA, the literature favours a midline incision and medial parapatellar approach, with lateral dislocation of the patella[8, 9, 83, 187, 291, 299, 300] though this can present difficulty accessing the lateral compartment. Others have described a mid-line incision then parallel medial and lateral parapatellar arthrotomies[143, 301], which Romagnoli et al. proclaimed offered the best protection to the extensor mechanism [143]. In the staged setting, Lustig et al. described making an incision parallel to the original scar, leaving a minimum 8cm gap[296], though others have reported necrosis if the skin bridge is compromised [304, 305] whilst Pandit et al.

described the addition of a UKA-L to an existing UKA-M by re-opening the previous skin medial incision, and extending proximally and distally, before entering the joint via a new lateral parapatellar arthrotomy[293].

The majority of studies utilise standard instrumentation, though more recently navigation and robotic arm-assisted techniques have been described[291, 306]. Biazzo, Manzotti and Confalonieri reported on 22 manually implanted Bi-UKA compared to 22 computer-navigated TKAs, reporting that at four-year follow-up Bi-UKA subjects had better WOMAC scores, less stiffness and significantly better function[290], later going on to report no long term differences in KSS, functional scores or WOMAC Arthritis Index (pain) between conventional Bi-UKA (n=19) to computer-assisted TKA (n=18)[307]. In the recently reported Total versus Robotic assisted Bi-UniCompartmental Knee (TRUCK) trial, Blyth et al. compared fixed-bearing primary Bi-UKA (n=34) implanted with the assistance of the MAKO robotic-arm (Stryker, USA) to mechanically aligned posterior-stabilised TKA implanted with conventional instrumentation (n=42)[308]. They found that Bi-UKA better maintains native kinematics whilst restoring coronal joint line obliquity and constitutional alignment[309] but that up to one-year post-surgery, outcomes between robotic-assisted Bi-UKA and conventional mechanically aligned TKA were comparable. Seven patients crossed over from Bi-UKA due to iatrogenic ACL injury or native ACL dysfunction found during surgery. No significant differences were found in PROMs at three months or one year. Operating times were significantly longer in the MAKO group, but in the first week following surgery Bi-UKA patients required fewer pain killers, were more comfortable and mobilised faster, though the differences did not reach significance and were potentially underpowered. Weaknesses of the study included patient selection, since not all subjects randomised to either group had bi-tibiofemoral OA, with some subjects in the Bi-UKA demonstrating radiographic evidence of PFJ OA which was not addressed surgically. The Bi-UKA group had a greater pre-operative requirement of walking aids, and that only the Bi-UKA group had robotic-assisted surgery[308].

3.5.2 Reported Outcomes of Primary Bi-UKA

Historical reports on the outcomes of primary Bi-UKA from Gunston[83], Walker et al[301] and Stockley et al.[300] reported significant pain relief, high patient satisfaction and significant functional improvements. Revision rates were variable, however. In Gunston's first series, one patient (4.5%) failed to benefit from functional improvement, going on to be arthrodesed[83]. Walker et. al reported 7.6% revision rate for loosening or infection[301]. Goodfellow and O'Connor reported up to 90% pain

relief, with restoration of mean 99° of flexion, but recurrent meniscal bearing dislocations and aseptic loosening of both femoral and tibial components led to failures in their cohort[187]. Barrett et al. reported 85% of patients undergoing mobile bearing Bi-UKA experienced significant pain relief[310]. Stokley et al. reported pain relief and functional improvement in 75% following Bi-UKA with a sledge prosthesis, but a 5.7% revision rate[300].

At 17 years, Parratte et al. reported 78% survival of fixed bearing Bi-UKA (16 revisions for aseptic loosening, one for progression of OA at mean 6.5 years) and significantly and persistently improved Knee Society and functional scores at 17 years[8]. Fuchs et al. reported functional outcomes of primary Bi-UKA to be similar to those of UKA-M[299] and retention of intraarticular ligaments results in near-native proprioception of the knee, compared to matched healthy subjects[311]. A number of studies have compared Bi-UKA to matched TKA, including Dettmer and Kreuzer, who reported significantly better Knee injury and OA outcome scores (KOOS) with Bi-UKA, along with fewer adverse symptoms and greater ability to engage in activities of daily living[291]. Confalonieri et al. recorded superior WOMAC scores, higher function, reduced stiffness and better overall alignment when comparing fixed-bearing Bi-UKA to matched TKAs[9].

3.5.3 Kinematics of Bi-UKA

Resultant kinematics following Bi-UKA have been reported by a number of authors, though the results are variable. Banks et. al[25], investigated the gait and kinematics of four Bi-UKA subjects and one subject with a TKA femoral component but medial and lateral tibial unicompartmental components, compared to contralateral healthy knees, UKA and TKA. Bi-UKA patients demonstrated higher knee flexion from heel-strike to mid-stance than TKA patients, but similar flexion in late stance through swing phase[312]. Fuch et al. demonstrated that Bi-UKA restores more normal kinematics compared to matched TKAs[299], whilst Watanabe et al. reported that Bi-UKA showed least posterior tibial translation during flexion, along with the least femoral external rotation when compared to UKA-M and BCA-M[313]. The kinematics of Bi-UKA with mobile bearing implants and/or staged Bi-UKA are comparatively under-reported.

3.6 Additional Considerations for CPKA

In health economic terms, in the primary setting, the surgeon must justify the cost of using of two primary implants, which are undoubtedly more expensive than a single TKA device. However, the implants themselves are fully licensed and readily available, so in comparison to bringing a new device to the market, with its associated research, development and licensing costs, increased uptake of CPKA is extremely cost-effective. Further, in comparison to the cost of revision to TKA, with the potential need for complex implants, prolonged length of stay, blood products for transfusion and significant rehabilitation, the cost of a second primary PKA implant signals a marked saving in favour of staged CPKA.

3.7 Compartmental Arthroplasty in Practice

The patients in the clinical elements of this thesis underwent primary or staged CPKA under the care of Professor Justin Cobb between 2010 - 2020. Over that time, practice evolved, to include the following:

3.7.1.1 Pre-operative assessment

The evolved indications for primary and staged CPKA in our practice are outlined in Table 3.1. In the primary setting, compartmental arthroplasty was considered when end-stage bone-on-bone contacts were confined to two compartments, with the articular tissues of the third compartment spared (cartilage and meniscus where applicable) in an otherwise stable knee. In the staged setting, conversion to CPKA was primarily indicated for bone-on-bone degeneration of one of the remaining compartments, where the third compartment was intact and disease-free on plain radiographs, and the ACL functional on clinical examination and radiographic imaging (<7mm anterior tibial translation[314]). The absence of a functional ACL was considered a relative contraindication to CPKA, permissible in some elderly patients, for example, where overall laxity of the joint was reduced, and the risk of major surgery was considered to outweigh the possibility of reduced anterior-posterior stability with PKA, primary CPKA or, in particular, staged CPKA, where revision to TKA may have posed considerable operative risk[174]. To date, inflammatory arthropathy has been considered a contra-indication due to the high probability of further degeneration of the remaining articular

tissues. Disease modifying anti-rheumatic drugs (DMARDs) have changed the natural history of inflammatory arthropathies and some patients are now developing non-inflammatory arthropathy as a result of degenerative ageing, despite well controlled inflammatory disease. Compartmental arthroplasty in these individuals may be an avenue to investigate in the future, but currently there is little evidence for its use. Therefore, within the context of this study, inflammatory arthropathy was considered a contraindication to CPKA.

	Indications	Contra-Indications
Primary	- Two compartment OA KL ≥ 3 - Spared third compartment (KL < 2) / no overt evidence of meniscal failure (if applicable) - Functional Anterior Cruciate Ligament* - Correctable varus to 15°	- Tricompartmental OA KL ≥ 3 or two-compartment OA with impending failure of third compartment - Significant laxity or instability - Anterior Cruciate Ligament dysfunction* - Inflammatory arthropathy
Staged	- Well-functioning primary PKA in situ^ - Osteoarthritic degeneration of a single native compartment - Intact articular tissues of the third compartment - Functional Anterior Cruciate Ligament* - Correctable varus / valgus deformity	- Loose / unstable / problematic primary partial knee arthroplasty^ - Osteoarthritic degeneration of two-native compartments - Anterior Cruciate Ligament dysfunction* - Inflammatory arthropathy - Evidence of periprosthetic infection

Table 3.1. Indications and Contra-indications for primary and staged CPKA.

*During this study, ACL dysfunction in the elderly was considered a relative contraindication, provided that the knee were otherwise stable. ^A worn polyethylene bearing may be exchanged at the time of second surgery and is not necessarily considered a contraindication.

Pre-operative imaging included plain radiographs of the knee, specifically the anterior-posterior, lateral, skyline and Rosenberg views. Magnetic resonance imaging for diagnostic purposes was not routinely used, as the primary indication for arthroplasty is KL ≥ 2, were typically evident on plain radiographs. The patients considered for this study routinely underwent low-dose computed tomography imaging of the hip, knee and ankle for pre-operative alignment and template planning (Embody Orthopaedic Ltd, London, UK).

3.7.1.2 Surgery

All procedures were performed under a tourniquet unless there was a specific reason not to use one. Instrumentation was conventional, multi-use, without robotic assistance. Primary CPKA procedures were performed through a midline incision. For BCA, a medial or lateral parapatellar approach was utilised as appropriate. In the relatively uncommon event of primary Bi-UKA, following the midline skin incision, separate medial and lateral parapatellar arthrotomies were performed as

this was considered less invasive than a large medial parapatellar approach, and balancing a UKA-L from the medial side is very difficult to achieve. In the staged setting, where conversion to BCA occurred, the original approach was re-opened and extended as required. During staged conversion to Bi-UKA, if the original incision was in the midline, it was re-opened, and a new parapatellar arthrotomy used to approach the native compartment (for example, a lateral parapatellar approach was used to approach the lateral compartment, even though the original procedure used a medial parapatellar approach to the medial compartment). If the original incision was medial or lateral to the midline, a new, parallel incision was made over the native compartment providing the skin bridge were sufficient to make necrosis unlikely. At present, no studies have investigated the most appropriate position of the implants with regard to each other and whether the position or orientation should be modified to account for the other implant. In lieu of this, each implant was placed in the optimal position for single implant surgery. In the Bi-UKA, the medial posterior tibial slope for the mobile bearing devices was cut at 7°, modified on a case-by-case basis according to pre-operative radiographs and native slope, whilst the lateral slope was cut at 3°. In the coronal plane, restoration of native joint line obliquity was preferred, typically in slight varus, for both medial and lateral tibial components[315].

3.7.1.3 Implants

Choice of implant evolved over the study period, in response to NJR data and implant availability. Therefore, there is implant variation in the patients included in the clinical studies of Chapters 6 and 7. All BCA-M and Bi-UKA patients in these studies underwent a mobile-bearing UKA-M (Oxford® Partial Knee, Zimmer Biomet). Of late, a change in practice has seen a move toward fixed bearing devices (Persona® Partial Knee, Zimmer Biomet, or JOURNEY UNI, Smith & Nephew) in elderly, lower demand patients, where wear may be less likely and the additional risk of bearing dislocation cannot be justified by functional gains, but no such patients are included in this thesis. BCA-L and Bi-UKA patients have a mix of mobile and fixed-lateral UKA devices. Previously, mobile bearings were preferred in the lateral compartment. However, NJR reports of high-rates of revision as a consequence of bearing dislocation resulted in a shift toward fixed bearing devices in 2017/2018, whereby the Fixed Lateral Oxford device (Oxford® Fixed Lateral Partial Knee, Zimmer Biomet) became the most common device to be implanted in the lateral compartment. There is most variation in the patellofemoral components. The Femoro-Patella Vialla (Wright Medical) and Sigma PFA (De Puy) were used in significant numbers, prior to their withdrawal from the market,

superseded by third generation onlay devices, most often the Zimmer® Gender Solutions™ PFA (Zimmer Biomet) or JOURNEY PFA (Smith & Nephew, Memphis, TN) depending on anatomy.

3.7.2 Post-Operative Rehabilitation

Patients were permitted to fully weight-bear immediately as able following surgery. Hospital discharge were dependent on satisfactory post-operative blood tests, radiographs excluding fracture, component misalignment or bearing dislocation, and safe mobilisation. Outpatient physiotherapy was not required in most patients. Early return to sport was cautious and advised on a case-by-case basis. After three months, patients were not subject to any specific limitations.

3.8 Chapter Summary

CPKA offers the surgeon a variety of options. In the primary setting, disease in two compartments in the presence of a functional ACL can be addressed through single-stage CPKA and there is some good evidence of success for this in the short to medium-term. Staged CPKA may be an appropriate alternative to revision to TKA in the event of native compartment degeneration following a well-functioning primary PKA. The addition of a second PKA preserves the primary PKA and restores function through a relatively small second procedure. Advocates of CPKA argue that, in tailoring the surgery to the exact disease pattern of the patient, further surgery may be avoided, and healthy bone and soft-tissues are preserved, minimising the risk to the patient and optimising function and satisfaction. If second surgery in PKA involves conversion to a standard primary TKA, this is usually relatively straightforward, involving primary TKA implants. The need for revision TKA may be delayed. Opponents, however, argue that total joint replacement removes the possibility of native compartment degeneration, thereby avoiding further surgery to address it.

Much of the evidence for BCA comes from the now historical monolithic implants. Relatively less is known about modular configurations. It is apparent, however, that clear nomenclature for these procedures is missing, and can make the evidence base confusing and difficult to follow. Relatively little is known of the biomechanics in respect to CPKA, in particular whether there is any evidence for reduced mid-flexion instability or whether CPKA can deliver a more powerful, efficient solution to multi-compartment OA. In vivo, it is unclear whether there is evidence of “high performance” associated with CPKA in either the primary or staged setting. How does the gait of CPKA compare to the healthy knee, and to the gold-standard treatment TKA? The impact of multiple-procedures on

functional outcomes and patient opinion is unclear, and few studies have reported patient satisfaction or quality of life following CPKA surgery. This thesis seeks to answer some of these questions.

4 The Language of Arthroplasty

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Garner A, van Arkel RJ, Cobb J. Classification of combined partial knee arthroplasty. Bone Joint J. 2019 Aug;101-B(8):922-928. doi: 10.1302/0301-620X.101B8.BJJ-2019-0125.R1. PMID: 31362558; PMCID: PMC6681677.

Garner AJ, Edwards TC, Liddle AD, Jones GG, Cobb JP. The revision partial knee classification system: understanding the causative pathology and magnitude of further surgery following partial knee arthroplasty. Bone Jt Open. 2021 Aug;2(8):638-645. doi: 10.1302/2633-1462.28.BJO-2021-0086.R1. PMID: 34392701; PMCID: PMC8384450.

Contributions

The majority of the work in this chapter was independent, however, the following people made certain, significant contributions:

- The MSk Lab 'Patient and Public Involvement Group' contributed towards the study design, relevance and data input – I am very grateful for their time and enthusiasm.

- Professor Justin Cobb, Mr Alex Liddle, Mr Gareth Jones and Mr Thomas Edwards contributed towards the surgical working groups and provided data, they all reviewed and edited the manuscripts.

- The work was supervised by Professor Justin Cobb and Dr Richard van Arkel. Dr van Arkel reviewed the data and edited the final manuscript for the first study.

The 'Revision Partial Knee Classification System' discussed in the second half of the chapter was externally validated by Professor David Murray, Professor Nick London, Professor Andrew Metcalfe, Mr Andrew Porteous and Dr Martin Roche

4.1 Motivation and aims

Orthopaedics has a long tradition of classification systems that help unify language, support efficient communication, guide treatment and indicate the likely prognosis or outcome of a musculoskeletal disease, injury or procedure [316]. Classification systems facilitate accurate medical note keeping, they justify clinical decision making, and enable to collection of data from one centre to another in a uniform way[316]. Classification systems go hand in hand with clinical coding, and remuneration. They must be reliable and reproducible.

At the outset of this project, two major issues were identified. First, it became evident that although a considerable amount of work had gone before regarding the use of two or more PKA implants in the same knee, there was little by way of consistency in the literature regarding the terminology used to describe and investigate their usage[317]. Second, in the case of a staged procedure for native compartment degeneration, the addition of a PKA to a knee with an existing PKA in the event of native compartment degeneration is not well described, such that at the outset of this PhD in 2017, the NJR were reporting on all their outcomes as 'revision total knee replacement' regardless of the actual procedure performed. Relatively small procedures are treated in the same way as operations needing augments and stems, which has implications for risk, recovery and health economics.

It became apparent that two classification systems would be useful, the first to name and abbreviate the use of two or more PKAs within the same knee, and the second, to accurately describe further surgery following PKA, taking account of the causative pathology and magnitude of the procedure.

4.2 Classification of Combined Partial Knee Arthroplasty

This section has been published and is reproduced here under the terms of the Creative Common Attribution Non-Commercial No Derivatives (CC BY-NC-ND 4.0) Licence: Garner A, van Arkel RJ, Cobb J. Classification of combined partial knee arthroplasty. Bone Joint J. 2019 Aug;101-B(8):922-928. doi: 10.1302/0301-620X.101B8.BJJ-2019-0125.R1. PMID: 31362558; PMCID: PMC6681677.

4.2.1 Abstract

Aims: There has been a recent resurgence in interest in combined partial knee arthroplasty (PKA) as an alternative to total knee arthroplasty (TKA). The varied terminology used to describe these procedures leads to confusion and ambiguity in communication between surgeons, allied health professionals, and patients. A standardized classification system is required for patient safety; accurate clinical record-keeping; clear communication; correct coding for appropriate remuneration; and joint registry data collection.

Methods: An advanced PubMed search was conducted, using medical subject headings (MeSH) to identify terms and abbreviations used to describe knee arthroplasty procedures. The search related to TKA, unicompartmental (UKA), patellofemoral (PFA), and combined PKA procedures. Surveys were conducted of orthopaedic surgeons, trainees, and biomechanical engineers, who were asked which of the descriptive terms and abbreviations identified from the literature search they found most intuitive and appropriate to describe each procedure. The results were used to determine a popular consensus.

Results: Survey participants preferred 'bi-unicondylar arthroplasty' (Bi-UKA) to describe ipsilateral medial and lateral unicompartmental arthroplasty; 'medial bi-compartmental arthroplasty' (BCA-M) to describe ipsilateral medial unicompartmental arthroplasty with patellofemoral arthroplasty; 'lateral bi-compartmental arthroplasty' (BCA-L) to describe ipsilateral lateral unicompartmental arthroplasty with patellofemoral arthroplasty; and tri-compartmental arthroplasty (TCA) to describe ipsilateral patellofemoral and medial and lateral unicompartmental arthroplasties. 'Combined partial knee arthroplasty' (CPKA) was the favoured umbrella term.

Conclusion: The terms bi-unicondylar arthroplasty (Bi-UKA), medial bicompartmental arthroplasty (BCA-M), lateral bicompartmental arthroplasty (BCA-L) and tricompartmental arthroplasty (TCA) are recommended as the preferred terms to classify CPKA procedures.

4.2.2 Background

In the last decade, 67 bicompartmental knee publications have been indexed in PubMed, compared with just eight in the period between 1998 and 2008. This still represents less than 0.5% of the 18,063 knee surgery publications from the proceeding decade.

4.2.3 Introduction

Using combinations of unicompartmental and patellofemoral implants to resurface damaged compartments in a targeted manner produces four possible implant configurations:

1. Medial and lateral unicompartmental arthroplasty
2. Medial with patellofemoral arthroplasty
3. Lateral with patellofemoral arthroplasty
4. Medial and lateral and patellofemoral arthroplasty.

At present there are a variety of terms and abbreviations used in the literature when referring to these procedures, which leads to confusion. The purpose of this study was to identify variants in terminology, descriptive terms, or abbreviations regarding “non-total knee arthroplasty” procedures, and then to use the most intuitive language in order to create a contemporary classification system. Failure to refer to this group of procedures in a consistent and accurate way is a potential patient safety issue as patients and healthcare professionals need to be clear as to exactly which procedure is planned, or has been performed, to provide safe and appropriate perioperative care[317]. Clinical records must be clear regarding which implant, or combination of implants, the patient has in situ, thus ensuring the hospital is remunerated appropriately for the treatment provided. Furthermore, surgeons and joint registries must be able to accurately log and account for these procedures to enable rigorous audit of outcomes.

4.2.4 Methods

An initial search using medical subject headings (MeSH), the National Library of Medicine’s controlled vocabulary thesaurus, was undertaken to determine whether accepted terminology existed for these procedures. An advanced search of PubMed (US National Library of Medicine National Institutes of Health) was undertaken, on 19 November 2018, to identify key descriptive terms relating to surgery of the knee. The advanced search included all titles and abstracts. The first search used the (<search term> AND knee AND arthroplasty), the second looked for (<search term> AND knee AND replacement), and the final was for (<search term> AND knee AND arthroplasty AND replacement) to identify any publications where the terms are used interchangeably. The chosen search terms, for the advanced search, were those identified from the MeSH search: knee; total; unicompartmental; partial; unicondylar; in addition to patellofemoral; uni-compartmental; small

implants; combined partial; compartmental; multi-compartment; bi-compartmental; bicompartmental; bi-unicondylar; biunicondylar; bi-unicompartmental; and biunicompartmental, which had not been identified in the MeSH search but considered relevant. The number of articles identified by the search was recorded. The PubMed advanced search function identifies only the articles which match all specified criteria, hence, a search for 'knee arthroplasty' and 'knee replacement' would identify only the articles which contained both terms.

The PubMed results were then sorted and filtered using the best match function to identify papers according to the search (bi-compartmental OR bicompartmental OR bi-unicondylar or bi-unicompartmental) AND knee AND (arthroplasty OR replacement). The top 15 papers were reviewed in full to determine the name given to each implant configuration, the abbreviation used, and whether the authors made a clear distinction between the use of a medial or lateral unicompartmental prosthesis when implanted in combination with patellofemoral arthroplasty.

The six terms and abbreviations used most commonly in the literature were then employed to create a survey, together with illustrations and radiographs demonstrating each combined arthroplasty procedure. Participants were asked to identify the one descriptive term and one abbreviation they felt were most intuitive for each procedure and for the combined procedures depicted by the illustration and radiographs. The survey was first circulated among 30 orthopaedic speciality registrars attending a training day. From their answers, a rationalised survey, using the top four preferred terms and abbreviations was created. The second survey was conducted at the International Society for Technology in Arthroplasty annual congress, held in London, United Kingdom (12^{th} – 18^{th} October 2018). A total of 200 surgeons and biomechanical engineers with a specialist interest in arthroplasty were invited to participate. The collective results were used to form a consensus regarding the most appropriate and intuitive terminology for each procedure.

4.2.5 Results

The MeSH search focused on 'arthroplasty, replacement, knee' and revealed 31 entry terms including arthroplasties, replacement, knee, total, partial, unicompartmental and unicondylar. The accepted MeSH search terms made no reference to patellofemoral arthroplasty or multiple partial knee arthroplasties used in combination in the same knee. The advanced search used the identified MeSH search terms, in addition to terms related to CPKA, and revealed that while both the terms 'arthroplasty' and 'replacement' were common, the term 'arthroplasty' was used more frequently (

Table 4.1). No clear distinction between the terms was found; indeed 3996 articles were found to have used both terms within the same title or abstract.

Search terms ('AND knee')	'AND arthroplasty' N =	'AND replacement' N =	'AND arthroplasty AND replacement' N =
MeSH terms			
Knee	23 463	11 529	3996
Total	19,195	8302	3470
Partial	435*	318*	103*
Unicompartmental	1429	587	322
Unicondylar	326	157	95
Uni-compartmental	12	6	4
Non-MeSH terms			
Patellofemoral	945	379	210
Small implants	2	3	1
Combined partial	34	1	0
Compartmental	89*	36*	15
Multi-compartment	1	0	0
Bi-compartmental	11	7	2
Bicompartmental	83	51	32
Bi-unicondylar	2	2	0
Biunicondylar	2	2	0
Bi-unicompartmental	4	5	2
Biunicompartmental	4	5	2

Table 4.1. Number of articles identified through a PubMed medical subject headings (MeSH) and advanced search of titles or abstracts containing descriptive terms for knee surgery *Search revealed a small number of unrelated articles. Data accessed 19 November 2018[77].

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A single implant resurfacing one tibiofemoral compartment was referred to as a 'unicondylar', 'uni-compartmental', and 'unicompartmental' procedure, though the latter was more frequent. The use of a hyphen was variable, more common in historical papers, and its use appears to have diminished with time. Partial knee arthroplasty (PKA) served as a commonly used umbrella term for procedures other than TKA, though the search did return papers referring to 'partial tendon ruptures' or 'partial cartilage loss' in relation to total knee procedures, so the true number is lower than the search numeric results suggest. Regarding CPKA, 'bi-compartmental' and 'bicompartmental' were used interchangeably, with the latter more commonly used to refer to knees where the patellofemoral joint and medial or lateral tibiofemoral joint had both undergone arthroplasty surgery. A significant number of papers referred to unicompartmental replacement without explicitly stating whether the medial or lateral compartment had been addressed. In the context of combined unicompartmental with patellofemoral arthroplasty procedures, there was rarely a distinction between medial and lateral unicompartmental replacement, which often needed to be established from the main text and led to significant confusion.

A very small number of papers were found to relate to ipsilateral medial and lateral unicompartmental replacement, without any real consensus. To describe this group of 'non-total' knee procedures collectively, 'compartmental' returned the greatest number of returns but was also elevated by papers referring to diseases of different compartments, rather than the procedures themselves.

The terminology and abbreviations used in the PubMed 'best match' papers varied greatly, which are detailed in Table 4.2. There was little consensus on the terminology for ipsilateral medial and lateral unicompartmental arthroplasty, with some preferring bi-unicompartmental[143, 318] while others used bi-uni[275] or bi-unicondylar[319]. This procedure was most commonly abbreviated to Bi-UKA or Bi-Uni. Others preferred to refer to all configurations as 'bicompartmental', explaining the exact configurations in parenthesis[8, 279, 288]. In reference to the Uni/PFA combination, almost all used 'bicompartmental' or less commonly bi-compartmental, with just one exception[293]. Most authors favoured 'BKA' as the abbreviation for this procedure. However, all but one publication[8]. failed to explicitly differentiate between medial or lateral unicompartmental arthroplasty when used in combination with patellofemoral arthroplasty, meaning that when the abbreviation was used, it was not immediately obvious whether the medial or lateral compartment had been resurfaced. With the exception of those papers describing monolithic components to simultaneously resurface the femoral condyle and trochlea, the majority of publications failed to state unequivocally whether both procedures had occurred under the same anaesthetic or whether a second operation had 'converted' a single previously performed partial arthroplasty to a combined procedure, as had exclusively been the case in one publication.[274]. Every publication analysed used parenthesis to explain their chosen abbreviation and the procedure in question, though there was little consensus or standardization.

Publication: First author and year	Medial and lateral unicompartmental; name (abbreviation)	Medial uni and patellofemoral arthroplasty; name (abbreviation)	Lateral uni and patellofemoral arthroplasty; name (abbreviation)	Clear distinction medial/lateral
Parratte, 2010[8]	Bicompartmental UKA (Bi-UKA)	Bicompartmental (med-UKA/PFA)	N/A	Yes
Spinelli, 2010[319]	Bi-Unicondylar (Bi-UKA)	N/A	N/A	N/A
Wünschel, 2011[257]	N/A	Bi-compartmental (BKA)	N/A	No
Chung and Min, 2013[283]	N/A	Bicompartmental (BKA)	Bicompartmental (BKA)	No
Thienpont and Price, 2013[320]	Bicompartmental (Bi-Uni)	Bicompartmental (BKA)	Bicompartmental (BKA)	No
Heyse, 2014[321]	N/A	Bicompartmental (BKA)	N/A	No
Kamath, 2014[322]	N/A	Bicompartmental (BiKA)	Bicompartmental (BiKA)	No
Parratte, 2015[275]	Bi-Uni (Bi-Uni)	Bicompartmental (BKA)	Bicompartmental (BKA)	No
Romagnoli, 2015[143]	Bi-unicompartmental (bi-UKR)	Combined uni and patellofemoral replacement (UKR+PFR)	Combined uni and patellofemoral replacement (UKR+PFR)	No
Yeo, 2015[323]	N/A	Bicompartmental (BCA)	N/A	No
Confalonieri, 2016[318]	Bi-Unicompartmental (Bi-UKA)	Bicompartmental (UKA+ PFA)	Bicompartmental (UKA+PFA)	No
Sabatini, 2016[274]	N/A	Bicompartmental (BKA)	Bicompartmental (BKA)	No
Ma, 2017 [288]	Bicompartmental (Bi-Uni)	Bicompartmental (BKA)	Bicompartmental (NLA)	No
Pandit, 2017[293]	Bi-Compartmental (Bi-UKA)	N/A	N/A	N/A
Wang, 2018[268]	N/A	Bi-Compartmental (BKR)	N/A	No

Table 4.2.Terminology and abbreviations used in the orthopaedic literature relating to combined partial knee arthroplasty. [77]

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A total of 28/30 orthopaedic speciality registrars familiar with unicompartmental, total knee, and patellofemoral procedures responded to the first survey. The terms ‘medial/lateral unicompartmental with patellofemoral replacement/arthroplasty’ and ‘bi-unicompartmental replacement/arthroplasty’ along with the abbreviations ‘UKA/PFA’, ‘UKR/PFR’, ‘BKR’, and ‘BUKR’ were found to be least favourable to the trainees and, therefore, were removed from the second survey. Out of a total of 200 participants invited to respond to the second survey, 62 biomechanical engineers, 35 senior orthopaedic surgeons, 16 orthopaedic speciality registrars and one industry representative took part. Overall, participants from the second survey preferred the term ‘arthroplasty’ to ‘replacement’ with 64% voting for ‘unicompartmental arthroplasty’ in preference to ‘unicompartmental replacement’. Similarly, 57% preferred ‘total knee arthroplasty’ to ‘total knee replacement’ and 57% opted for ‘patellofemoral arthroplasty’ in preference to ‘patellofemoral replacement’. Collectively, 54% of first and second survey participants preferred ‘partial knee arthroplasty (PKA)’ to ‘partial knee replacement (PKR)’ (46%) when describing a single compartment

procedure. Similarly, 54% felt ‘combined partial knee arthroplasty (CPKA)’ was more intuitive than combined partial knee replacement (CPKR) (46%), compartmental replacement (0%), or multicompartment replacement (0%) when describing the use of more than one small implant in the same knee.

Responses from the first and second survey are shown in Figure 4.1. Arthroplasty descriptions were preferred, as were hyphenated descriptions. Medial bi-compartmental arthroplasty; lateral bi-compartmental arthroplasty and bi-unicondylar arthroplasty proved most popular. Extended descriptions, for example ‘medial unicompartmental with patellofemoral arthroplasty’ and other such combinations were not found intuitive. Regarding abbreviations, survey respondents found BCA-M, BCA-L, and Bi-UKA preferable. UKA/PFA, UKR/PFR, BUKR, and BKR received no votes. Two senior surgeons from the second survey thought that ‘Bi-UKA’ referred to bilateral UKA, specifically one UKA in the right knee and one in the left. The term ‘BKA’ was commonly used in the literature (Table 4.2), but caused significant discussion. 14 speciality registrars (six from the first survey and seven from the second survey) and five senior orthopaedic surgeons from the second survey commented that they commonly abbreviated ‘below knee amputation’ to ‘BKA’, which they identified as possibly becoming a major source of confusion. All votes for ‘BKA’ came from biomechanical engineers in the second survey, with no surgeons preferring this abbreviation to the others suggested.

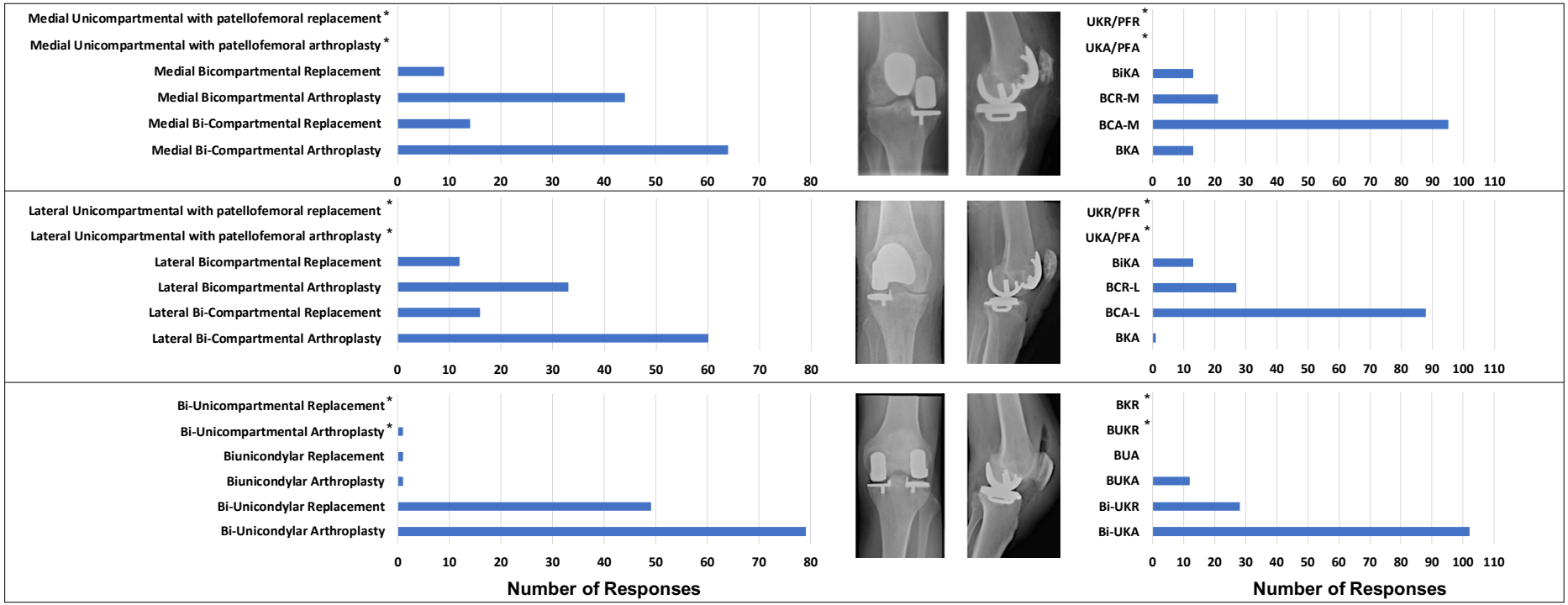


Figure 4.1.Collective results of the two surveys completed by orthopaedic speciality registrars (survey 1) and orthopaedic surgeons, speciality registrars and arthroplasty biomechanical engineers (survey 2) regarding terminology and abbreviations for combined partial knee arthroplasty procedures. *Excluded from second survey. [77]

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Based on our findings, the following terms and abbreviations are recommended: total knee arthroplasty (TKA); unicompartmental knee arthroplasty (UKA); patellofemoral arthroplasty (PFA); partial knee arthroplasty (PKA) as the umbrella term for UKA or PFA. We propose the terms medial bicompartmental arthroplasty (BCA-M) to describe an ipsilateral medial UKA plus PFA; lateral bicompartmental arthroplasty (BCA-L) to describe ipsilateral lateral UKA plus PFA; bi-unicondylar arthroplasty (Bi-UKA) to describe ipsilateral medial and lateral UKA; and tricompartmental arthroplasty (TCA) to describe all three in combination (Figure 4.2). The most intuitive umbrella term for Bi-UKA, BCA-M, BCA-L, and TCA collectively is combined partial knee arthroplasty (CPKA).

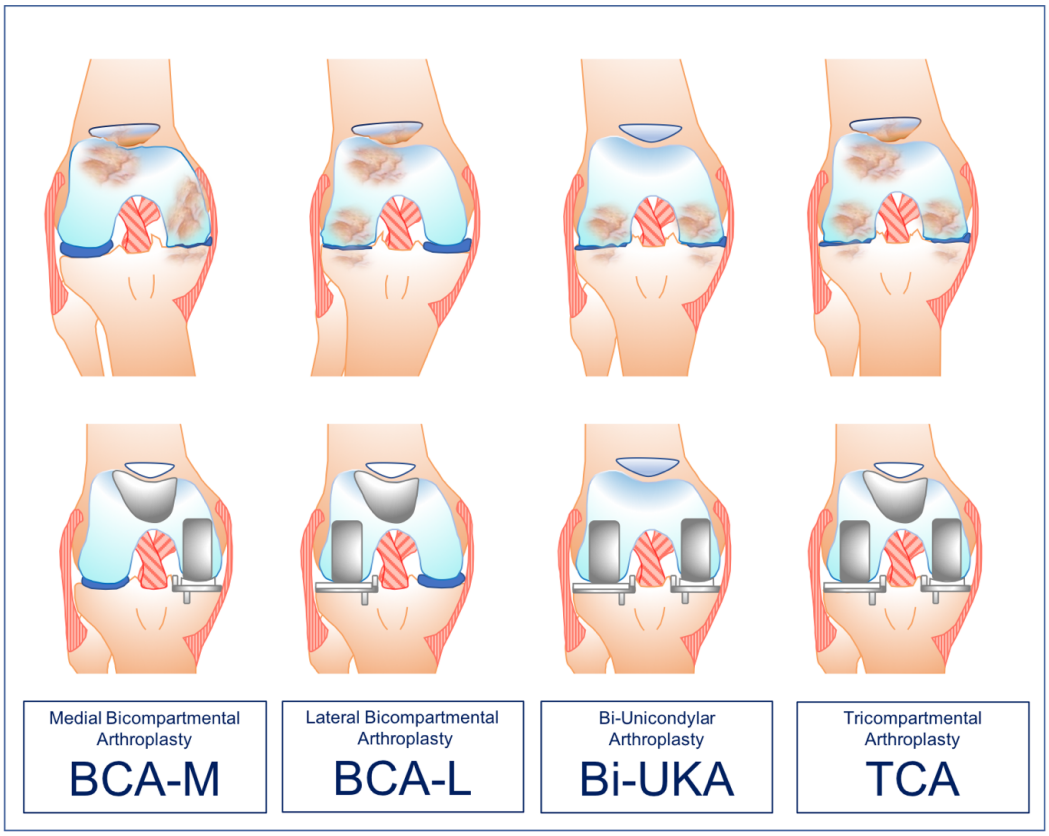


Figure 4.2.Classification of combined partial knee arthroplasty (CPKA). [77]

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4.2.6 Discussion

Unsurprisingly, inconsistent terminology runs throughout knee surgery literature, leading to confusion and uncertainty. Uniform descriptions and abbreviations are essential for clear communication and cohesive understanding. While TKR/TKA and UKR/UKA are generally understood, they are used interchangeably for no obvious reason. The term ‘arthroplasty’ was used

twice as often in the literature as ‘replacement’ in both its complete and abbreviated form. Similarly, ‘arthroplasty’ was preferred by our cohort of orthopaedic surgeons and biomechanical engineers. The term ‘replacement’ overlooks re-surfacing procedures, particularly in partial knee surgery, for example, which may be one explanation for the discrepancy.

The different configurations of CPKA were poorly defined with limited consensus in the scientific literature on appropriate abbreviations. Version 7.0 of the knee form K1 from the National Joint Registry, released in June 2018, allows surgeons to record that more than one PKA procedure has been performed in the primary setting[179]. Similarly, version 7.0 K2 now includes the option to record ‘partial replacement second compartment of knee’, in recognition of the additional small implant[324]. As accurate analysis of this data becomes possible, many more publications in the field of CPKA are likely to follow. Clear definitions enable communication, allowing the reader to gain accurate insight into the literature as to exactly which procedure is being discussed. The interchangeable use of ‘bicompartmental’ and ‘bi-unicondylar’ with their numerous associated abbreviations, with and without hyphens, were found to be a significant source of confusion to the survey participants. Despite ‘bicompartmental’ being found most commonly in the literature, the survey respondents leaned more towards the hyphenated form ‘bi-compartmental’. The term ‘unicompartmental’ is relatively undisputed, which is why its counterpart ‘bicompartmental’ is used most often in the published form. However, our respondents also preferred the hyphenated ‘bi-unicondylar’ term, which may have biased them towards other hyphenated forms. As seen with uni-compartmental and unicompartmental, history suggests that where there is no convention in the English language for the use of a hyphen, it tends to be abandoned over time, which is an argument to avoid its use for bicompartmental procedures, as is currently the case in the literature.

The abbreviations ‘Bi-UKA’, ‘BCA-M’ and ‘BCA-L’ were preferred and considered intuitive to the procedures they describe, clearly differentiating between medial and lateral unicompartmental procedures and distinguishing the ‘Uni/PFA’ combination from the ipsilateral medial and lateral unicompartmental procedure. The abbreviation ‘BKA’ though is long-established in English medical literature to describe a below knee amputation[325, 326].

Our numeric PubMed search results considered only study titles and abstracts and in doing so may have inadvertently overlooked detailed definitions explained by authors in their sub-text, limiting this study. The survey method stops short of a formal Delphi survey since the first group of respondents were not true experts in this specific area of arthroplasty surgery. The lack of joint

registry data relating to combined procedures makes identifying surgeons regularly performing these procedures more difficult. In this paper we have set out to design a classification system that is clear and user-friendly to the wider orthopaedic community. For this reason, we chose to survey orthopaedic surgeons and biomechanical engineers with a specialist interest in arthroplasty technology, as these individuals are stakeholders in the final outcome. Clear preferences were demonstrated by the respondents, giving us confidence that the proposed classification system will be acceptable to users. The options offered to participants came from frequently cited papers in this field, but there are no doubt other alternatives, which this study did not consider. The respondents in the second-round survey were attending an international conference, in London and conducted in English; therefore, the relevance of this study to non-UK, non-English speaking practice may be limited.

Accurate classification of these procedures will improve written and verbal communication between surgeons, allied health professionals and patients, making certain that the patients understand the arthroplasty options available to them[178]. A robust classification system ensures accurate clinical coding for remuneration, individual surgeon logbook data and joint registry audit, to meet modern patient safety standards.

4.2.7 Reflections upon the study

This study was conducted in 2018. It was published in The Bone & Joint Journal in August 2019[77], featuring in the editorial of that edition[317]. It has since been downloaded more than 2300 times and cited 16 times. The design of the study uses a "popular vote" to identify preferred outcomes within a knowledgeable but not expert population. An alternative design would be to have taken a consensus of expert opinion from those who regularly perform or research these procedures. The outcome of such a study may have yielded different results, in particular the controversial distinction between arthroplasty and revision surgery, and the overall umbrella term. Of note, at the time of the survey, patients with multiple PKA implants within the same knee were not described in any major implant registry, including the National Joint Registry for England and Wales[327]. In 2020 the term 'multicompartmental replacement' entered the NJR report for the first time. Whilst it is excellent progress that these procedures are finally being recognised and data pertaining to them expeditiously collected, the term chosen by the NJR had never appeared in the literature before and received 0% of the votes during this current study. Whilst Combined Partial Knee Arthroplasty was the preferred umbrella term by respondents, 'multi-compartmental' arthroplasty is intuitive and

self-explanatory. The intention of this study was to unify language. The NJR's preferred terminology of 'multi-compartmental arthroplasty' appears now to be the internationally accepted term, though the individual descriptors of bicompartmental and Bi-Unicondylar and their associated acronyms BCA-M, BCA-L and Bi-UKA are retained and preferred.

4.4 Classification of Revision of Partial and Combined Partial Knee Arthroplasty

4.4.1.1 Publications:

This section has been published and is reproduced here under the terms of the Creative Common Attribution Non-Commercial No Derivatives (CC BY-NC-ND 4.0) Licence: Garner AJ, Edwards TC, Liddle AD, Jones GG, Cobb JP. The revision partial knee classification system: understanding the causative pathology and magnitude of further surgery following partial knee arthroplasty. Bone Jt Open. 2021 Aug;2(8):638-645. doi: 10.1302/2633-1462.28.BJO-2021-0086.R1. PMID: 34392701

4.4.1.2 Abstract:

Aims: Joint registries classify all further arthroplasty procedures to a knee with an existing partial arthroplasty as revision surgery, regardless of the actual procedure performed. Relatively minor procedures including bearing exchanges are classified in the same way as major operations requiring augments and stems. A new classification system is proposed to acknowledge and describe the detail of these procedures, which has implications for risk, recovery and health economics.

Methods: Classification categories were proposed by a surgical consensus group, then ranked by patients, according to perceived invasiveness and implications for recovery. In round one, twenty-six revision cases were classified by the consensus group. Results were tested for inter-rater reliability. In round two, four additional cases were added for clarity. Round three repeated the survey one month later, subject to inter- and intra-rater reliability testing. In round four, five additional expert partial knee surgeons were asked to classify the 30 cases according to the proposed RPKC system.

Results: Four classes were proposed: PR1 where no bone-implant interfaces are affected, PR2 where surgery does not include conversion to total knee replacement, for example, a second partial arthroplasty to a native compartment; PR3, when a standard primary total knee prosthesis is used; and PR4 when revision components are necessary. Round one resulted in 92% inter-rater agreement (Kendall's W =0.97, $p<0.005$), rising to 93% in round two (Kendall's W =0.98, $p<0.001$). Round three demonstrated 97% agreement (Kendall's W =0.98, $p<0.001$), with high intra-rater reliability (Interclass Correlation Coefficient = 0.99, 95% Confidence Interval 0.98-0.99). Round four resulted in 80% agreement (Kendall's W=0.92, $p<0.001$).

Conclusions: The Revision Partial Knee Classification System accounts for all procedures which may be appropriate following partial knee arthroplasty. It has been shown to be reliable, repeatable, pragmatic. The implications for patient care, and health economics are discussed.

4.4.2 Introduction

Partial knee arthroplasty (PKA) is revised more frequently than Total Knee Arthroplasty (TKA) as reflected by joint registries across the world[5, 6, 180]. The complexity of PKA revision can vary significantly: for example, a patient undergoing exchange of polyethylene bearing, will likely have very different perioperative risks and post-operative rehabilitation regimen compared to a PKA revised to a TKA with a revision implant, stems and metaphyseal augments[328]. Progression of arthritis in a native compartment is one of the most common causes of revision of PKA, usually addressed by removal of the existing PKA components and conversion to TKA[236]. The alternative stepwise 'compartmental approach' is poorly defined[317]. Currently, National Joint Registry (NJR) revision rates for PKA do not differentiate between these different types of revision procedure.

A number of studies have indicated that thresholds for revision may be lower for UKA than for TKA[182, 183, 236, 329]. The National Institute for Clinical Excellence (NICE) recently highlighted the disparity in threshold for revision rate between PKA and TKA and the size of the interventions, and suggested that revisions should be separated into major and minor procedures[330]. When judged in terms of safety and cost-effectiveness, PKA dominates, with better health outcomes and reduced lifetime costs compared to TKA[331]. PKA is also associated with fewer post-operative complications[174], higher patient reported satisfaction[229] and shorter hospital stays[175]. The cost burden for revision of knee arthroplasty is significant, and correlates with the complexity of the second procedure[332, 333].

The varying complexity of revision following primary total arthroplasty was recognised in a recently published revision knee complexity classification (RKCC). In this paper, revisions were subcategorised according to 6 variables: integrity of the soft-tissue envelope, presence of infection, patient factors, the requirement for augmented implants, metaphyseal reconstruction, and hinged or stemmed implants[334].

The RKCC reduced these to three categories of revision:

R1 (less complex): revision of primary unicompartmental or TKA, aseptic loosening, simple instability, revision of partial to TKA, or polyethylene exchange.

R2 (complex): includes knees with significant instability, the need for metaphyseal fixation, re-revisions or those requiring enhanced exposure techniques.

R3 (most complex): multiple re-revisions, those requiring a hinge or where salvage, arthrodesis or amputation may be required.

The causative pathology, variety and complexity of surgery following PKA do not fit well into this system - many appear more minor than R1, while others are clearly R2. It became apparent that a classification system specific to further surgery following PKA would have a use - preoperative decision making might be improved by detailing the complexity of planned revision of PKA, as RKCC recommends for revision of TKA[334]. By paying particular attention to the mode of failure of the primary procedure; the underlying pathology and complexity of revision of PKA, our primary aim was to produce a robust and usable system to classify these further surgical procedures. Our secondary aim was to help appreciate the impact of the different classes of procedure, something which is often not reflected in existing tariffs for revision of a primary knee arthroplasty[335].

4.4.3 Methods

This study did not require institutional review board approval. The proposed system was conceived, modified and tested for reliability according to the step-wise process shown in Figure 4.3.

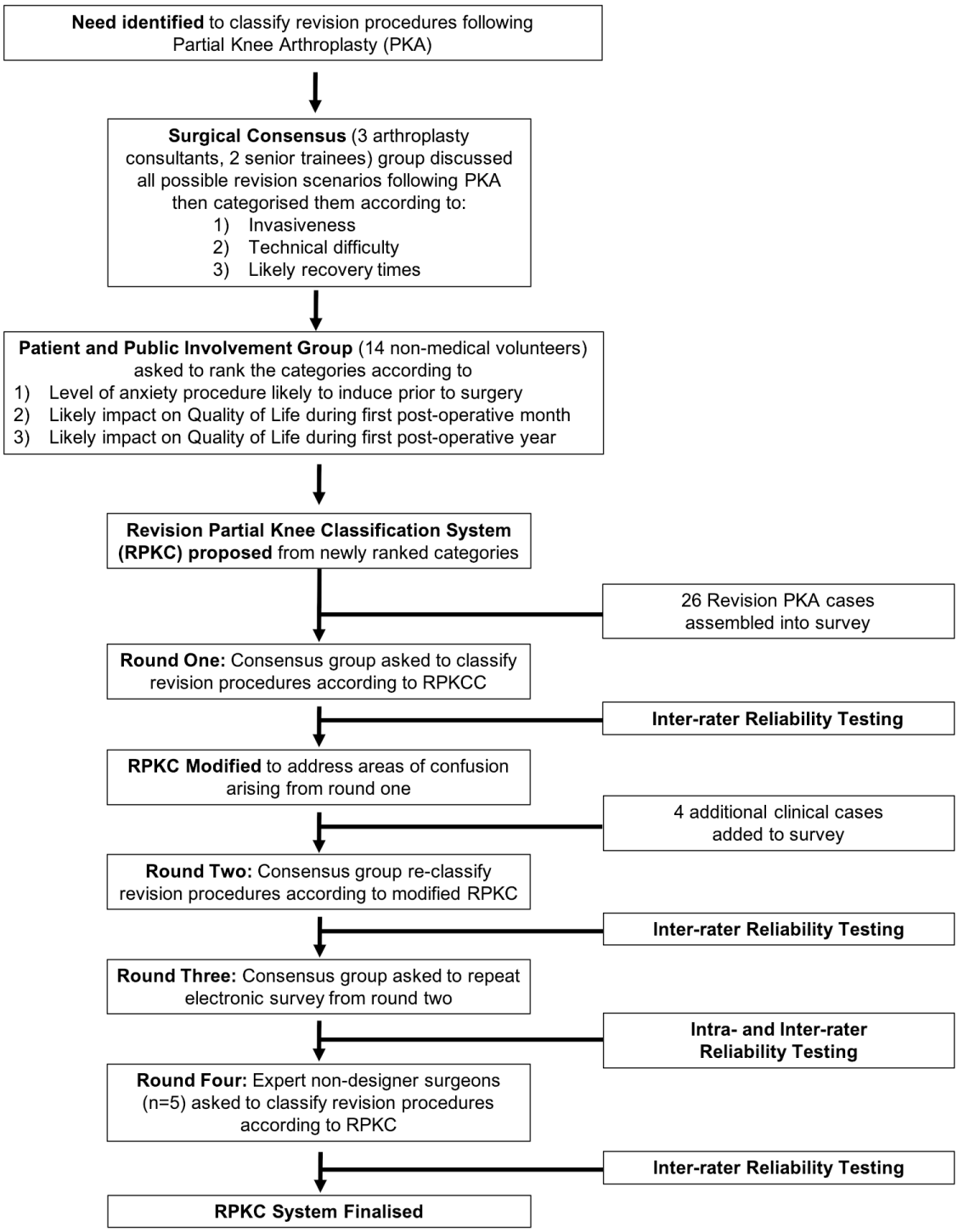


Figure 4.3. Flow diagram of the Process of Creation and Reliability Testing of the proposed Revision Partial Knee Classification System. [181]

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First, a collaborative consensus group met, consisting of three orthopaedic consultant surgeons experienced in primary and revision knee arthroplasty surgery (Professor Justin Cobb, Mr Alex Liddle and Mr Gareth Jones), myself and another orthopaedic higher speciality trainee (Mr Thomas Edwards) with each of us having more than five years of arthroplasty experience. Our group was asked to consider all possible modes of failure, including implant wear, loosening, native compartment degeneration, instability, stiffness and pain, then list all potential revision procedures, categorising them according to underlying causative pathology, technical complexity, invasiveness of the procedure and anticipated recovery times. It was agreed that the principles of the classification should be:

1. A reproducible, reliable grading system
2. That each grade reflects the magnitude of undertaking for the patient and the technical complexity of the procedure for the surgeon
3. Incorporation of other grading systems: e.g. Anderson Orthopaedic Research Institute (AORI) classification of bone loss[336] and the Revision Knee Complexity Classification System[334]
4. To facilitate a discussion regarding the level of expertise required to manage each case.

Accordingly, our consensus group resolved upon five revision categories, with the procedures in each category perceived to be of similar surgical complexity. Anonymised case reports of each of these categories were then presented, in a randomised unranked order, to a patient and public involvement (PPI) group. The PPI group consisted of fourteen non-medical volunteers, some of whom had previously undergone hip and knee arthroplasty procedures. Medical terminology was explained in plain, non-technical English and picture form. Descriptions including the size of the wound; extent of soft-tissue dissection; length of procedure; length of hospital stay; post-operative mobilisation regimen and rate of return to routine activities. The PPI group volunteers were then asked to individually rank the categories, according to three criteria:

1) the severity of the proposed surgical procedure, leading to the level of anxiety such a procedure would likely cause them prior to surgery (1 = least anxiety, 5 = most anxiety inducing).
2) the impact of the procedure on quality of life in the first 30 days post-surgery (1 = least impact, 5 = most impact)
3) the impact of the procedure on quality of life in months 2-12 post-surgery (1 = least impact, 5 = most impact).

4.4.3.1 Testing the Proposed RPKC System

Results from the PPI rankings were used to inform the development of the RPKC classification system, which was then tested for inter-rater reliability. Hospital operating lists from the past 12 months revealed that 26 cases had undergone revision of PKA. These were collated into an anonymised encrypted electronic survey, which included clinical and radiological information and the revision procedure performed.

4.4.3.1.1 Round One

The electronic survey of 26 cases was distributed amongst the five members of the surgeon consensus group. Blinded to the identity of the patient, respondents were asked to classify the revision procedure. The order of cases presented to each respondent was randomised. Where disagreement was found, the consensus group was asked to clarify the wording of the classification category and where disagreement occurred, additional similar cases were added to clarify the criteria and validate the category.

4.4.3.1.2 Round Two:

The original 26 cases, plus four additional cases added for clarification, were included in round two, which was conducted one month after round one. The order of cases was re-randomised and respondents were once again asked to classify the proposed revision surgery according to the RPKC system.

4.4.3.1.3 Round Three

Since there had been significant changes to the wording of the classification system and additional cases added between rounds one and two, a third round was conducted one month after round two.

4.4.3.1.4 Round Four

In the final round of testing, the survey of 30 cases was disseminated to a group of five world-leading experts in partial knee arthroplasty (Professor David Murray, Professor Nick London, Professor Andrew Metcalfe, Mr Andrew Porteous and Dr Martin Roche). The electronic survey was

identical to the version used in rounds two and three. The experts had not been part of the design or creation of the proposed classification system, but were asked to comment on it and suggest modifications where they felt appropriate. The expert surgeons were asked to classify each case according to the management plan proposed by the MDT.

4.4.4 Statistical Analysis

Estimation of inter-rater reliability was conducted, after each round of testing, using Kendall's Coefficient of Concordance, W (Kendall's W)[337, 338]. Intra-rater reliability, using the Interclass Correlation Coefficient (ICC), was used to compare responses between rounds two and three. For round four, the inter-rater reliability was calculated using Kendall's W, first amongst the expert non-designer surgeons themselves, and then for the consensus group plus the expert surgeon group.

4.4.5 Results

The surgeon consensus group agreed on four partial revision categories (Table 4.3):

1) when no revision of any bone-implant interface is performed, such as a bearing change or ACL reconstruction, or fracture fixation with implant retention.
2) when bone surgery is involved but the ACL is preserved, avoiding a TKA
3) when a TKA is required using a primary TKA device
4) when stems, augments or supplemental metaphyseal fixation are required

Category	Description of revision procedure by category	Rank Pre-op Anxiety	Rank QoL (1st Month)	Rank QoL (2-12 Months)	Proposed Class
A	• No removal of metal components, Polyethylene exchange • Ligament Repair / Reconstruction (E.g., ACL, MPFL) • Debridement with implant retention (DAIR) for acute infection	1.14 ± 0.36	1.21 ± 0.43	1.0 ± 0	PR1
B	• Addition of partial knee to one native compartment (primary procedure unchanged) • Revision of one metal component for pain, instability, or loosening (e.g. conversion from mobile to fixed bearing tibial component)	2.0 ± 0.55	1.79 ± 0.43	2.21 ± 0.43	PR2a
C	• Addition of partial knees to two native compartments (primary procedure unchanged) • Addition of partial knee to the remaining native compartment of a knee previously subject to a PR2a (addition of partial knee to one native compartment) procedure. • Revision of two or more metal components to another PKA for pain, instability, loosening or malalignment	2.86 ± 0.36	3.07 ± 0.27	2.93 ± 0.62	PR2b
D	• PKA to TKA with AORI 1 or 2A (no requirement for supplemental metaphyseal fixation)	4.0 ± 0	3.93 ± 0.27	3.93 ± 0.47	PR3
E	• PKA to TKA with AORI 2B/3 (requirement for supplemental metaphyseal fixation) • Requirement for augments, stemmed or hinged prosthesis • Requirement for enhanced exposure techniques such as tubercle osteotomy	5.0 ± 0	5.0 ± 0	4.93 ± 0.27	PR4

Table 4.3 Mean scores with standard deviations ranked by patient and public involvement group volunteers (N = 14). 1 = least impact on anxiety levels and quality of life (QoL), 5 = greatest impact.[181]

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After discussion, 2 was subdivided into 2a, when a single component of a PKA was revised, or an additional PKA was added (Figure 4.4), or 2b for anything more complex than this, when the ACL is preserved, and monolithic femoral or tibial components are avoided (Figure 4.5)

When presented with these different classes in random order, the PPI group scored the classes using the three metrics: severity of surgical procedure, short term impact of surgery on the patient, and longer-term impact on quality of life. Their scores on all counts increased with the grade of procedure. PR1 procedures ranked lowest, scoring 1.14 ± 0.36 for operative severity, 1.21 ± 0.43 for short term impact and 1.0 for long term impact, while PR4 scored 5 for severity, and short-term impact, and 4.9 for longer term impact (Table 4.3). Although the PPI group scored PR2b as a more major procedure than PR2a on all three scales, the group felt that implant procedures which did not result in total knee replacement should be grouped together in a single group, PR2 for ease of understanding. The name 'Revision Partial Knee Classification' System (RPKC) was proposed, to follow the precedent set by the RKCC system.

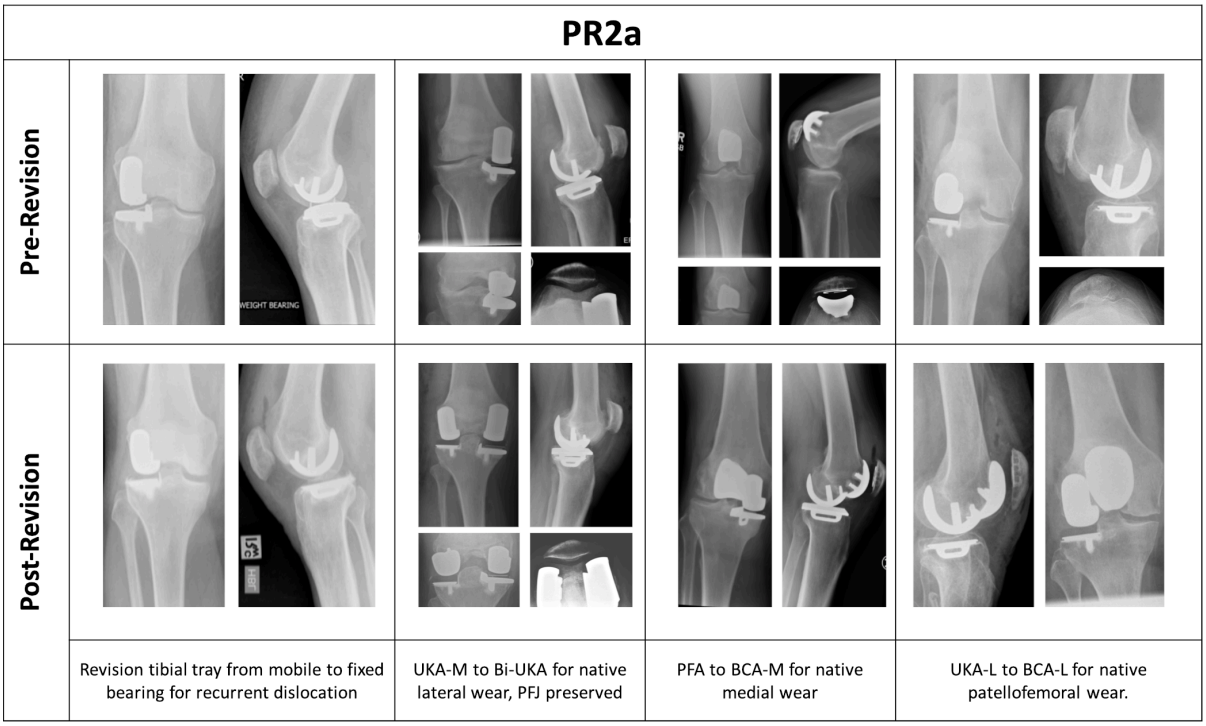


Figure 4.4. Radiographic Examples of PR2a Procedures Pre- and Post-Revision Surgery[181].

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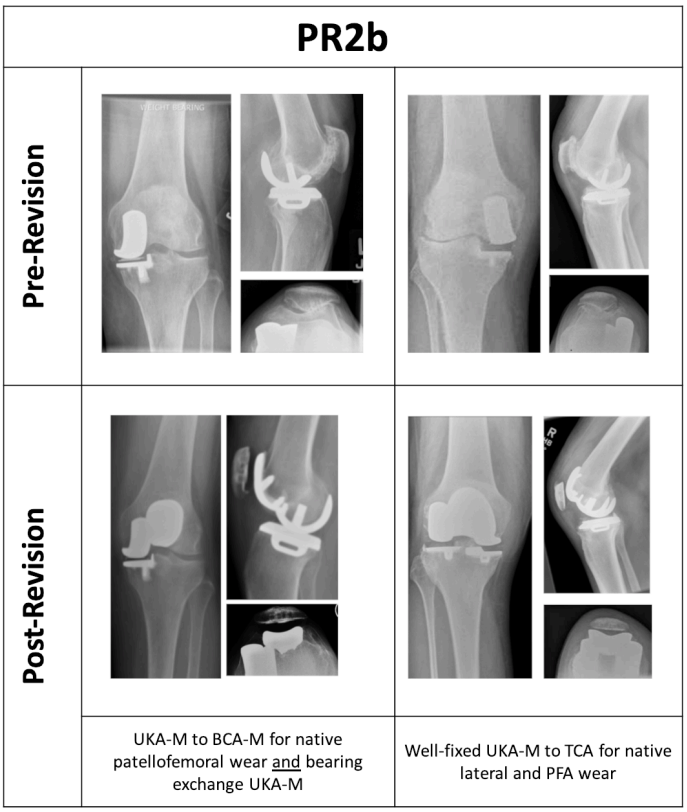


Figure 4.5.Example of PR2b Procedures Pre- and Post-Second Surgery [181]

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4.4.5.1 Reliability Testing

Revision Partial Knee Classification System (RPKC)
PR1 – Revision Partial 1
Joint Registry Procedures: - UKA Polyethylene exchange - No removal of metal components *Non-Joint Registry Procedures:* - Ligament Repair / Reconstruction (E.g. ACL, MPFL) - Debridement with implant retention (DAIR) - Fracture Fixation – all components left in situ
PR2a – Revision Partial 2a
- Addition of partial knee to one native compartment (primary procedure unchanged) - Revision of one metal component e.g. conversion from mobile to fixed bearing tibial component - Revision of patella button)
PR2b – Revision Partial 2b
- Addition of partial knees to two native compartments (primary procedure unchanged) - Addition of partial knee to the remaining native compartment of a knee previously subject to PR2a - Revision of two or more components (e.g. femoral and tibial components) - Cases simultaneously undergoing an ipsilateral PR1 and a PR2a procedure
PR3 – Revision Partial 3
- PKA to standard TKA implant, with AORI 1 or 2A: no augments, stemmed implants or supplemental metaphyseal fixation
PR4 – Revision Partial 4
- PKA to TKA with AORI 2B/3 (requirement for supplemental metaphyseal fixation) - Requirement for augments, stemmed or hinged prosthesis - Requirement for enhanced exposure techniques such as tubercle osteotomy

Figure 4.6. The newly proposed Revision Partial Knee Classification System[181]

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The newly-defined RPKC system (Figure 4.6) consists of four classes: PR1 – PR4. Class PR2a and PR2b are within the same class PR2 on the advice of our PPI group. Round one of reliability testing consisted of an electronic survey of 26 cases. Kendall's W was used to determine if there was agreement between the five surgeons' judgement of revision class. The surgeons agreed on 24/26 cases, Kendall's W = 0.97, p = <0.0005 (Table 4.4). Consequently, agreement between surgeons can explain 96.5% of all possible variability, concluding that agreement between raters is 'very good'[339]. Disagreement was observed in two of the 26 questions. The first of these related to exchange of a patella button, with the senior trainees both regarding this as a 'PR1' revision, with the understanding that this was exchange of polyethylene, whilst all three consultants regarded this as a component revision, although the original wording related to a 'metal component'. A further consensus meeting concluded that removal of the patella button was a more technical procedure than exchange of a meniscal bearing, and may require augmentation of the remaining patella, hence it should be included in PR2a. The word 'metal' was subsequently removed from the description of PR2a and 'revision of patella button' included in parenthesis. The second case which divided opinion

regarded the choice of prosthesis for revision of a UKA to TKA. In this particular case, the surgeon opted for a standard primary TKA femoral component but used a short stem extension on the tibial component, without the need for augmentation; bone grafting; metaphyseal sleeves or cones. One consultant and one trainee ranked this as a PR3, whilst the remaining two consultants and one trainee ranked this as a PR4. During the second consensus meeting, it was agreed that the additional wording of PR3 be amended to 'PKA to standard TKA, with AORI 1 or 2A (no requirement for augments, stemmed implants or supplemental metaphyseal fixation) be inserted into the description of a PR3 revision to resolve this ambiguity.

Round	Cases (N =)	Agreement (%)	Inter-Rater Reliability			Intra-Rater Reliability	
			Kendall's W	p value	Reliability	ICC	95% CI
One	26	92.3	0.97	< 0.0005	Very Good		
Two	30	93.3	0.98	< 0.001	Very Good	0.99	0.98 – 0.99
Three	30	96.7	0.98	< 0.001	Very Good		
Four	30	80	0.92	< 0.001	Very Good		

Table 4.4. Results of intra- and inter-observer reliability testing of proposed RPKCC System. ICC: Interclass Correlation Coefficient. [181]

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The issues raised during round one were clarified and round two was conducted one month later. For round two, raters were in agreement on 28/30 cases (93%, Kendall's W = 0.98, p<0.001). In round three, raters agreed on 29/30 cases (97%, Kendall's W = 0.98. p<0.001, Table 4.4), Intra-rater reliability between rounds two and three demonstrated excellent agreement with narrow confidence intervals (ICC = 0.99, 95% Confidence Interval 0.98-0.99, Table 4.4)

In round four, all five members of the expert non-designer surgeon group completed the electronic survey. The expert surgeons were in agreement for 24/30 cases (80%, Kendall's W = 0.87, p<0.0001) Of the remaining 6 questions, four of the five surgeons were in agreement in all cases, though the one in disagreement were not always the same surgeon. When all responses were analysed for the consensus designer-surgeon group together with the expert non-designer surgeon group, respondents were in agreement for 24/30 cases (80%, Kendall's W = 0.92, p<0.0001).

4.4.6 Discussion

This study set out to classify revision procedures following PKA. The RPKC appears to be simple, robust and reliable, allowing patients, surgeons and commissioners of healthcare to appreciate the complexity and costs of the different procedures. The validation process returned Kendall's W scores above 0.92 in all four rounds, suggesting "very good" inter-rater reliability for both the designer surgeon consensus group and a group of expert PKA surgeons whom had not been involved in the design or creation of the RPKC system.

By describing the different procedures, with a rising level of complexity and cost, NICE's recommendations can be easily realised. The insight of our PPI group seems reasonable: procedures where the original PKA and ACL are left undisturbed should be considered relatively minor, while conversion to TKA or beyond should be considered major. This framework may contribute to the recommendation from NICE, allowing revision surgery to be reported accurately, and enabling the surgeon to make decisions based upon clinical need and patient safety. Detail regarding the nature of further surgery is imperative to understand and interpret big data sets such as the NJR.

Across the whole of medicine, classification systems are properly based upon pathology, given that this is usually the determinant of prognosis. Systems that focus on the magnitude and complexity of surgery or the impact on patient anxiety levels and post-operative quality of life, have also been shown to be useful tools in patient-surgical decision making, clinical prioritisation in resource-limited health care systems and appropriate remuneration[77, 334, 340, 341]. The proposed RPKC system follows this philosophy. It has been designed by surgeons, patients and public volunteers, and validated by expert surgeons in the field of partial knee arthroplasty, to reflect the causative pathology, complexity, magnitude and likely impact on patient anxiety levels and post-operative quality of life following revision of a PKA. Patient perceptions of surgery have been shown to have a significant impact on recovery and willingness to undergo future procedures. By asking the PPI group to 'rank' their perceptions on the magnitude of surgery, in the short and medium term, we were able to classify the invasiveness of each class. Well informed patients tend to make better decisions regarding their care, and recover faster as they know what to expect from the process[342-344].

4.4.6.1 Limitations

This study has certain limitations. First, the consensus group was small, and a wider group of opinions may be required to formally adapt and mould the classification system into its final iteration, although the five independent world experts did not suggest any further modifications. Second, all classification systems are subject to interpretation and surgeon choice. There is a significant difference in 'severity' between a simple liner exchange and an ACL reconstruction or tibial plateau fracture fixation, yet all sit best as PR1, since none require the removal or replacement of metallic arthroplasty components. However, the short- and medium-term impact on quality of life and implications for recovery would likely be quite different. The difference between PR3 and PR4 may be vulnerable to surgeon choice and preference. Whilst significant bone loss may require additional constraint; stems or metaphyseal augments, it is possible that surgeons may prefer them or choose to use them routinely when revising PKA, even if a standard TKA implant may suffice[236]. Finally, further surgery as a result of periprosthetic joint infection does not immediately fit into any one particular category and, therefore, must be assessed on a case-by-case basis depending on the management of that case. Infection of PKA is, itself, quite rare, however, a DAIR, for example, would likely be PR1, whilst a two-stage revision would likely be PR4. Although it is entirely possible to revise an infected UKA to a standard primary TKA prosthesis, the outcomes may well be worse than revision of a PKA to a highly constrained hinge, for example, for instability secondary to medial collateral ligament failure[236].

4.4.7 Conclusion

This classification of further surgery following PKA is reliable, reproducible and pragmatic. The system compliments other, more established, systems including AORI and RKCC. It may help patients understand the different modes of failure of primary PKA and the options available for second surgery, in line with the principles of GIRFT. This system may prove useful for more detailed audit of joint registry data to better understand the relatively higher rates of PKA revision compared to TKA. For health economists and health-care providers, the proposed classification system might assist

4.5 Chapter Summary

Two new classification systems have been proposed to address specific issues. The 'Combined Partial Knee Arthroplasty Classification' system has been devised by consensus, to enable the accurate description of the status of patients with multiple PKA implants within the same knee. Meanwhile, the causative pathology and magnitude of further surgery following primary PKA can now be discussed, using the common language proposed through the 'Revision Partial Knee Classification' system. This system may prove useful for more detailed audit of joint registry data to better understand the relatively higher rates of PKA revision compared to TKA. For health economists and health-care providers, the proposed classification system might assist with more accurate coding and appropriate remuneration of smaller safer procedures, when compared with larger more expensive ones of limited effectiveness.

5 The Biomechanics of Compartmental Arthroplasty

Publications

This chapter includes text and images from the following publications, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Partial and Combined Partial Knee Arthroplasty: Greater Anterior-Posterior Stability Than Posterior Cruciate-Retaining Total Knee Arthroplasty. J Arthroplasty. 2021 Jun 29:S0883-5403(21)00585-4. doi: 10.1016/j.arth.2021.06.025.

Garner A, Dandridge O, Amis AA, Cobb JP, van Arkel RJ. The extensor efficiency of unicompartmental, bicompartmental, and total knee arthroplasty. Bone Joint Res. 2021 Jan;10(1):1-9. doi: 10.1302/2046-3758.101.BJR-2020-0248.R1.

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Dandridge O, Garner A, Amis AA, Cobb JP, van Arkel RJ. Variation in the patellar tendon moment arm identified with an improved measurement framework. J Orthop Res. 2021 Jun 30. doi: 10.1002/jor.25124.

Dandridge O, Garner A, Jeffers JRT, Amis AA, Cobb JP, van Arkel RJ. Validity of repeated-measures analyses of in vitro arthroplasty kinematics and kinetics. J Biomech. 2021 Aug 2;129:110669. doi: 10.1016/j.jbiomech.2021.110669.

Contributions

This work was largely collaborative. The following people made significant contributions to this section:

1. Conception and design of the studies
    - With Professor Justin Cobb, Dr Richard van Arkel and Professor Andrew Amis

2. Re-design and adaptation of the Extension Rig, modification of Kinematics Rig.
    - Predominantly Amy Garner, supported by Dr Richard van Arkel

3. Preparation of the cadavers
    - Predominantly Amy Garner, supported by Oliver Dandridge

4. Surgical procedures: Amy Garner, supervised initially by Professor Justin Cobb, then independently once technique approved by Professor Cobb and Mr Tim Lawes (Zimmer Biomet representative). Oliver Dandridge acted as the surgical assistant in all cases.

5. Collection of the data
    - Extensive equal collaboration with Oliver Dandridge

6. Analysis of the data
    - Bespoke Matlab script written by Dr Richard van Arkel and Oliver Dandridge
    - Statistical analysis and interpretation of the data: predominantly Amy Garner supported by Oliver Dandridge and Dr Richard van Arkel
    - Graphical representation of the data: design brief: Amy Garner and Dr Richard van Arkel, creation of graphs Oliver Dandridge and Amy Garner, editing and interpretation of the graphs Amy Garner

7. Writing of chapters and manuscripts: as per order of authorship for each publication

8. Editing and reviewing of chapters and manuscripts: Dr Richard van Arkel, Oliver Dandridge, Andrew Amis and Professor Justin Cobb

Ethical Approval

Ethical approval was granted by Imperial College Health-care Tissue bank Project R15022 and HTA License 12275

Definitions

For the purposes of this thesis, the following definitions will be used:

Laxity:	The passive response of a joint to an externally applied load [345]
Active Stability:	The ability of the joint to maintain its original position when subject to an external load, through the action of muscles and their aponeuroses
Passive stability:	The ability of the joint to maintain its original position when subject to an external load, as a consequence of bone morphology, cartilage shape and integrity, menisci and ligament function.
Instability:	A functional measure of the sensation of “giving way”
Static Test:	Testing of a joint at a fixed position when subject to a specific load
Dynamic Test:	A continuous measurement of the joint throughout a range of motion or when subjected to a range of loads

5.1 Introduction

Understanding the biomechanical properties of the knee joint in different implant states offers the opportunity to gain insight into how and why the knee behaves as it does *in vivo* and helps to frame the observed differences in functional and clinical outcomes. To date, we have limited data on the biomechanics of combined partial knee arthroplasty. Functional gait relies on complex biomechanics, but two properties are of particular importance: anterior-posterior stability and extensor mechanism efficiency. The following studies seek to better understand the biomechanics of PKA and CPKA, comparing them to those of the native knee and to cemented, fixed-bearing, posterior-cruciate retaining TKA, the best performing, most implanted TKA device in the NJR[76] . Particular attention is paid to the extensor mechanism and to anterior-posterior stability. Cadaveric testing lends itself to the investigation of stability and efficiency - tests can be a combination of static strain gauge readings at different angles in the flexion-extension cycle, and dynamic motion capture, as the knee is passively moved throughout the range of motion

5.2 Methods

5.2.1 Preparation of Cadaveric Specimens

Fresh-frozen cadaveric knees (mid-femur to mid-tibia) were sourced from Science Care™ Inc, USA, who consented the donors for research and screened the specimens for HIV-1 / HIV-2 / Hepatitis B and Hepatitis C. An equal number of men and women were requested, aged 55-75 years old at death, with a body mass index less than 30kg/m^2. The past medical history was reviewed prior to accepting the specimens: all had died from medical causes unrelated to musculoskeletal health. The donors had no history or visible signs of previous knee surgery, trauma, alignment issues, metastatic cancers which potentially affect bone, Paget's disease or inflammatory conditions including Rheumatoid Arthritis or Psoriatic arthropathy. The original plan had been for the specimens to be paired from the same donor: right knee specimens to be used for procedures based around the medial compartment and the left for the lateral equivalents. However, two specimens were deemed unsuitable for testing – one was found to have a tibial fracture on computed tomography prior to testing and during testing one knee, once fully prepared, was found not to be able to reach full extension in the native state, presumably due to a degree of stiffness and reduced range of motion prior to death. Therefore, these specimens were replaced, hence, paired testing was no longer

possible. However, since we were not directly comparing medial to lateral procedures, it was deemed that this was not likely to significantly change the outcome.

Specimens were stored in a medical grade refrigerator at -24° Celsius until testing. For each round of testing, the selected specimen was defrosted at room temperature for 18-24 hours. Initial dissection involved removing the skin and subcutaneous fat, whilst carefully preserving the fascia. The femur was cut 20cm from the joint line then the proximal 5cm were placed in a cylindrical pot, held in place with bone cement. Projecting from the end of the pot was a bolt, in line with the long axis of the femur, which subsequently enabled the specimen to be mounted on the test rigs. The tibia was cut 16cm distal to the joint and stripped of all distal muscular attachments. An intramedullary rod was inserted into the tibia, at the maximum diameter the isthmus would accommodate, held in place by a distal transcortical interference screw. The fibula was cut 5cm distal to its proximal head and screwed to the tibia, using a 4.5mm fully-threaded cancellous screw, to maintain the anatomy and function of the lateral collateral ligament[346, 347].

Testing required individual loading of the quadriceps tendons; iliotibial band and hamstring tendons. The tendons were individually dissected, stripped of muscle fibres and bound in fabric[346, 347]. Rectus Femoris and Vastus Intermedius were bound together, whilst Vastus Medialis Longus (VML); Vastus Medialis Obliquus (VMO); Vastus Lateralis Longus (VLL); Vastus Lateralis Obliquus (VLO) and the Iliotibial Band (ITB) were bound individually. Posteriorly, semimembranosus and semitendinosus were bound together to form a medial hamstring bundle, whilst the long and short heads of biceps femoris were bound together laterally[348]. Cables were attached to the bound fabric, to facilitate loading.

5.2.1.1 Transpatellar Approach to the Joint

The stated arthroplasty series required repeated access to the joint, made possible using a sagittal transpatellar approach was used to enable repeated access to the knee without the need to transect the extensor retinacula, necessitated by the parapatellar approach[349]. This method enables in vitro investigation without measurement artefact due to variance in suture tension following surgical repair[349]. Stage one was to drill two parallel holes across the patella, from lateral to medial, approximately 10mm apart. The patella osteotomy was made in the sagittal plane, 10mm from the lateral border of the patella, using a reciprocating saw. The final cut through the cartilage is made with a sharp scalpel, so as to make a clean cut and protect the underlying structures. The extensor

split was continued into the quadriceps and patella tendons in line with the fibres of the tendons (Figure 5.1A). The joint can then be accessed to perform the arthroplasty procedures.

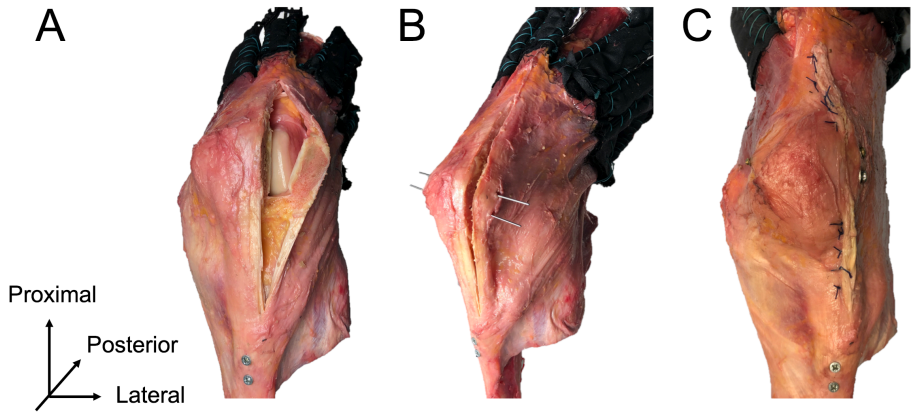


Figure 5.1.Cadaveric specimens depicting sagittal transpatellar osteotomy with quadriceps and patellar tendon splits to approach the knee joint (a) K wires passed across the patellar (b) Reduction with partially threaded cannulated screws and tendon sutured repair (c)

At the end of the procedure, the arthrotomy was closed, first by passing two 1.1mm k-wires through the pre-drilled holes (Figure 5.1B), then reducing the osteotomy with 3.5mm partially threaded cannulated cancellous screws, with washers, passing from lateral to medial, so that the threads of the screws had purchase in the medial fragment (Figure 5.1C and Figure 5.2). Care was taken to ensure the screws were sufficiently anterior so as not to become exposed when the bone cut for the patella button was performed during the later patellofemoral arthroplasty. The tendon splits were opposed using 3.0 Vicryl® (Ethicon inc. New Jersey, USA) interrupted sutures (Figure 5.1C). When subsequent access to the joint was required, the screws were removed and the sutures individually cut.

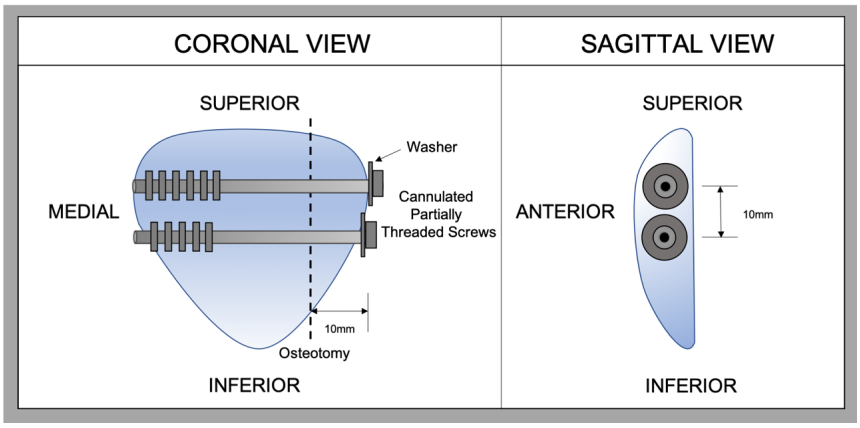


Figure 5.2. Schematic representation of transpatellar sagittal osteotomy 10mm from lateral margin, reduced with two partially threaded cannulated cancellous screws with washers spaced 10mm apart

With regards to implantation of the patella button during the test sequence (Section 8.6.2.4) the patella button was fixed to the medial fragment, with all three pegs located in the fragment where possible. In the rare instances where fixation of all three pegs was not possible, the peg in the over-hanging section of the button was removed. Similarly, when fixation of the button to the medial fragment alone was deemed to "over medialise" the button, the button was either downsized, or a small portion was left exposed laterally, which then interacted with the lateral patella fragment once the osteotomy was reduced. Alignment and accurate button positioning was prioritised, as was restoration of native patella height, as measured with callipers pre-patella cut and post-patella button implantation (Figure 5.3).



Figure 5.3. Cadaveric knee specimen with total knee replacement in situ (lateral view) Particular attention is paid to the patellar button position relative to the transpatellar osteotomy

5.2.1.2 Preparation for Optical Tracking

Fiducial markers were sited to enable registration of 14 bony landmarks for optical tracking. Ten 15mm screws were placed, in the following locations, in addition to the heads and tips of the transpatellar partially threaded cancellous screws:

5) Femur:
    a. Proximal anterior femoral shaft
    b. Medial Epicondyle
    c. Lateral Epicondyle
6) Tibia:
    a. Medial condyle
    b. Lateral condyle
    c. Tibial Tuberosity
    d. Anterior tibial spine 10mm distal to tibial tuberosity
    e. Distal anterior tibial spine distal

7) Patella:
    a. Proximal pole
    b. Distal pole
    c. Medial border proximal screw tip
    d. Medial border distal screw tip
    e. Lateral border proximal screw head (deepest point of Hex)
    f. Lateral border distal screw head (deepest point of Hex)

Each marker represented a bony prominence, which, when digitised, enabled a co-ordinate reference frame to be established, between the femur, tibia and patella, as previously described [350]. The insertion points of the patellar tendon on the distal pole of the patella and tibial tubercle were also digitised. Using the method described by Krevolin et al.[351] the moment arm can be calculated by tracking the knee movement through the full flexion-extension arc, measuring at 100 increments. A bigger moment arm will demonstrate a more efficient extensor mechanism.

Pilot testing was conducted using the Polaris Vega® Optical tracking system (NDI, Ontario, Canada). However, space constraints on both the rig and in the laboratory meant it proved impossible to track the complete range of motion required (0-110°). Therefore, for the main testing, the OptoTrak Certus (NDI, Ontario, Canada) system was used. This system requires a clustered LED tracking device in each moving segment. In order to capture the full range of motion, two LED clusters were placed in each bone, at different angles to each other (Figure 5.4).

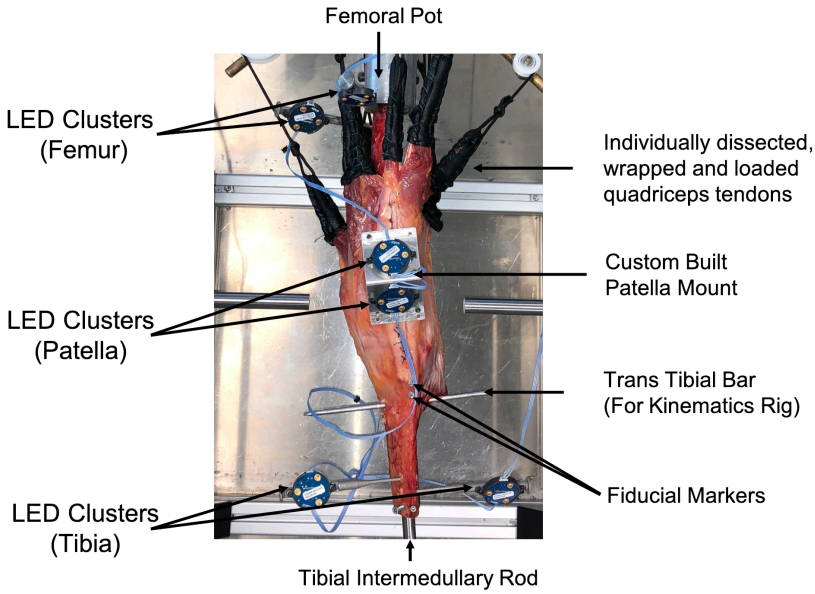


Figure 5.4. Locations of LED clusters on the dissected specimen (here shown in full extension mounted on the extension rig with the tendons fully loaded)

Two patellar LED clusters were mounted on a custom-built mount (Figure 5.5, Figure 5.7), attached via a custom-built block (Figure 5.6). The mounting block was placed on the anterior aspect of the patella using two 10mm screws. Pilot testing with and without this block suggested that the additional weight of the mount on the patella accounted for minimal error.

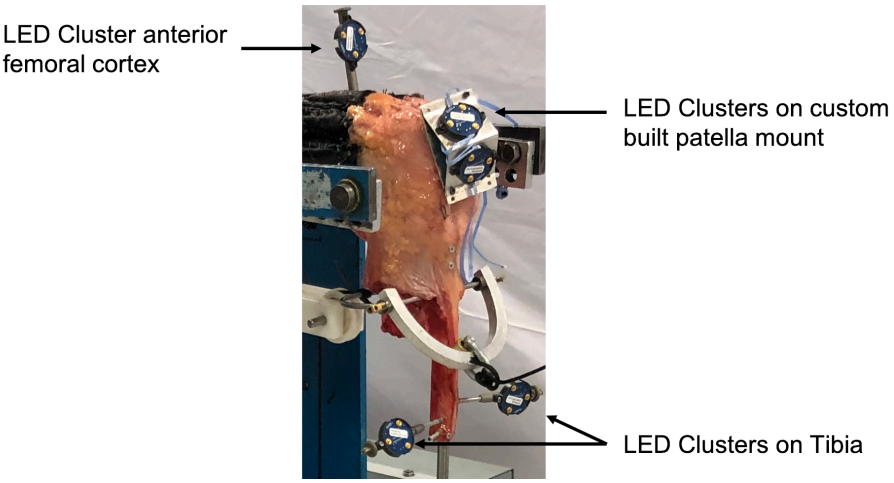


Figure 5.5. Knee specimen mounted on kinematics rig, showing custom-built patella mount with two LED Clusters. Femoral and tibial LED clusters also shown.

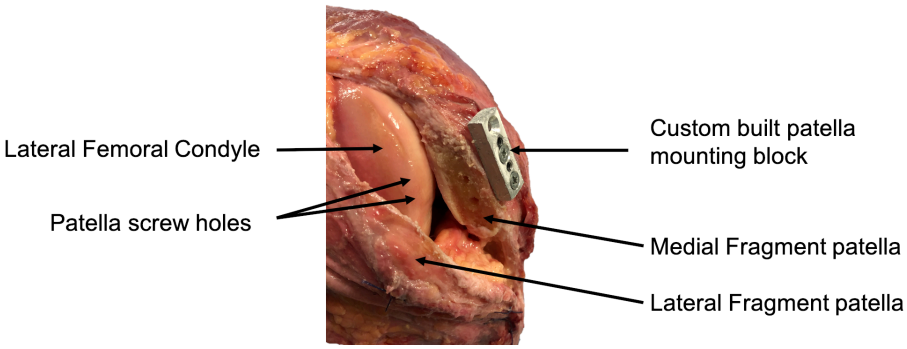


Figure 5.6. Knee specimen from the lateral aspect, exposed through transpatellar approach, showing custom-built patella block, attached to the anterior aspect of the medial fragment of the patella.

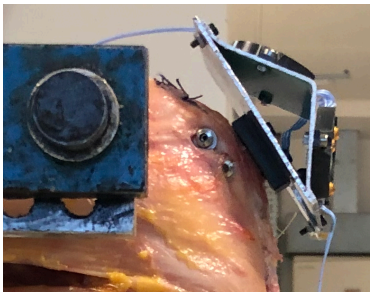


Figure 5.7. Knee specimen from lateral aspect, demonstrating the bespoke patella mount with two LED Clusters for Motion Tracking

5.2.2 Arthroplasty Procedures

5.2.2.1 Pre-operative Planning

The specimens underwent Computed Tomography scanning in their frozen state. Segmentation was conducted manually (Figure 5.8) using Mimics 3D Medical Image Processing Software (Materialise, NV, USA). The segmented scans were then used assess native joint line obliquity and preferred implant sizes and positions, using Embody Orthopaedic Ltd (London, UK) software to match the Oxford® Partial Knee System (Zimmer Biomet, Warsaw, USA) (Figure 5.9).

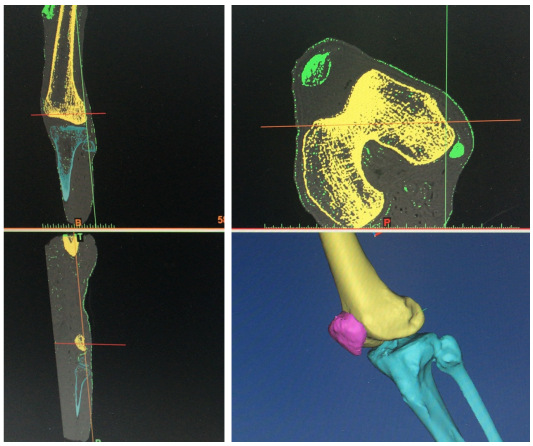


Figure 5.8. Manual segmentation of CT scan of cadaveric knee, using Mimics 3D Medical Image Processing Software (Materialise, NV, USA)

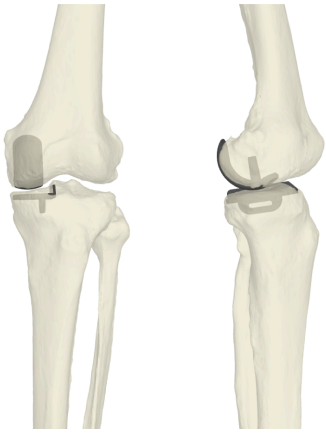


Figure 5.9. 3D Pre-operative planning of medial unicompartmental arthroplasty using Embody Orthopaedic (London, UK) planning software.

5.2.2.2 Instrumentation

All arthroplasty procedures were carried out using standard instrumentation, without patient specific instrumentation or robotic assistance. A mobile-bearing UKA was used for all medial compartment procedures (Oxford® Partial Knee System, Zimmer Biomet Warsaw, Indiana, USA). The tibia was cut with a seven-degree posterior slope, and balanced in flexion and extension, according to the tension of the medial-collateral ligament. Joint line obliquity was restored to native varus of between 0-3 degrees, based on the pre-procedure scans. Implants were cemented in situ, with sufficient bone cement to secure the implants, but without significant bony penetration in order to preserve the underlying bone bed for later implant removal. For the lateral tibiofemoral joint, a fixed bearing UKA was used (Fixed Lateral Oxford, Oxford® Partial Knee System, Zimmer Biomet Warsaw, Indiana, USA). A three-degree posterior slope was cut, and the flexion gap intentionally 2mm greater than the extension gap to account for native lateral tibiofemoral laxity.

The addition of a PFA to the UKA in groups one and two converted the state to a BCA. The PFA (Gender Solutions™ patellofemoral arthroplasty, Zimmer Biomet, Warsaw, Indiana, USA) was anterior referenced and orientated to the transepicondylar axis and native trochlear groove without notching. The patella button was sized according the native patella: height was restored using calliper measurements to avoid over-stuffing. For the final round of testing, all metallic PKA components were carefully removed using a fine saw blade at the cement-bone interface to protect the underlying bone bed, which was inspected to ensure it was in satisfactory condition, without the need for augments, wedges or additional constraint, which it was in all cases (Figure 5.14). A mechanically aligned cemented primary posterior-cruciate retaining TKA (NexGen® CR-Flex Zimmer Biomet, Warsaw, Indiana, USA) was implanted, using a gap-balancing technique and three-degree posterior slope. The thickness of the TKA polyethylene bearing was 10mm in 15 knees, 12mm in 8 and 14mm in 1, selected to ensure equal flexion and extension gaps and appropriate soft-tissue tension, in particular the medial collateral ligament. The sequence of arthroplasty procedures (Figure 5.13) necessitated that once implanted, the patella button should not be removed. The design of the Zimmer™ Gender Solutions® PFA matches the geometry of the anterior flange of the NexGen® CR-Flex TKA device (Zimmer Biomet), therefore, it was planned that the conversion of BCA to TKA would preserve the implanted patella button.

All implants were hospital-grade. The metallic components were re-used between specimens where sizes would allow, but once implanted, the patella button was not removed - a new button was used

for each specimen. The cemented versions of each implant were used, with sufficient polymethyl methacrylate bone cement to ensure stability, but less than would be used in vivo, in order to be bone-preserving at the point of removal. Although the Cementless Oxford has seen a dramatic increase in use clinically, it was not deemed necessary for these experiments, since the 'joint facing' geometry is standardised between the Cemented and Cementless components; Cementless is more expensive and a tight press-fit may risk fracture or bone loss at the point of removal.

5.2.2.3 Alignment

Since the knee specimens were mid-femur to mid-tibia, certain adaptations were necessary to ensure accurate implant alignment: on the femoral side, an intramedullary alignment technique was used in all procedures, but with the shorter of the two intramedullary rods provided with each instrument set. On the tibial side, extra-medullary alignment was preferred. In vivo, this requires the ankle to be present, however, in its absence, a bespoke 3D printed device (Figure 5.10) was designed and used to align the tibial cutting jigs to the intramedullary tibial rod. Two versions were printed; one specific to the Microplasty® jig (Figure 5.10 and Figure 5.11) and the NexGen® jig (Figure 5.12). Intentionally, the tibial intramedullary rod was as large as the medullary canal could accommodate to ensure press-fit and alignment with the long axis of the tibia as far as was possible. The extramedullary tibial jig passed through the 3D printed device, which itself clipped on to the intramedullary tibial rod. The device could be extended as required to enable to posterior slope of the tibial cut to be increased or decreased as desired.

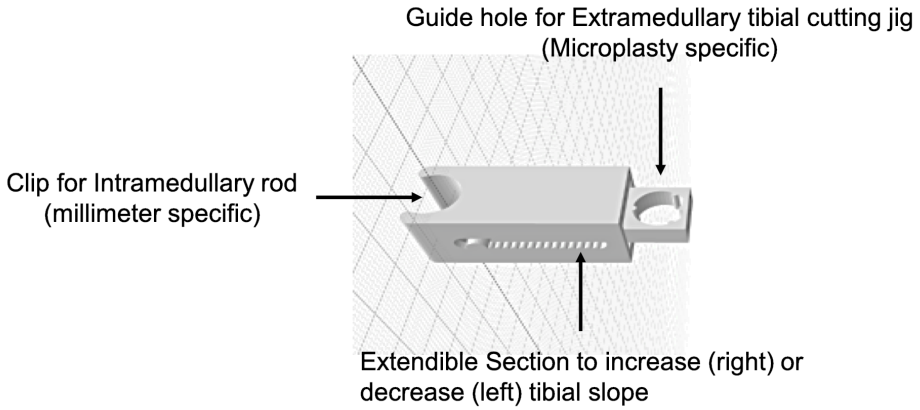


Figure 5.10. Computer Assisted Design model of 3D printed bespoke alignment device, here shown as the Microplasty® specific version.

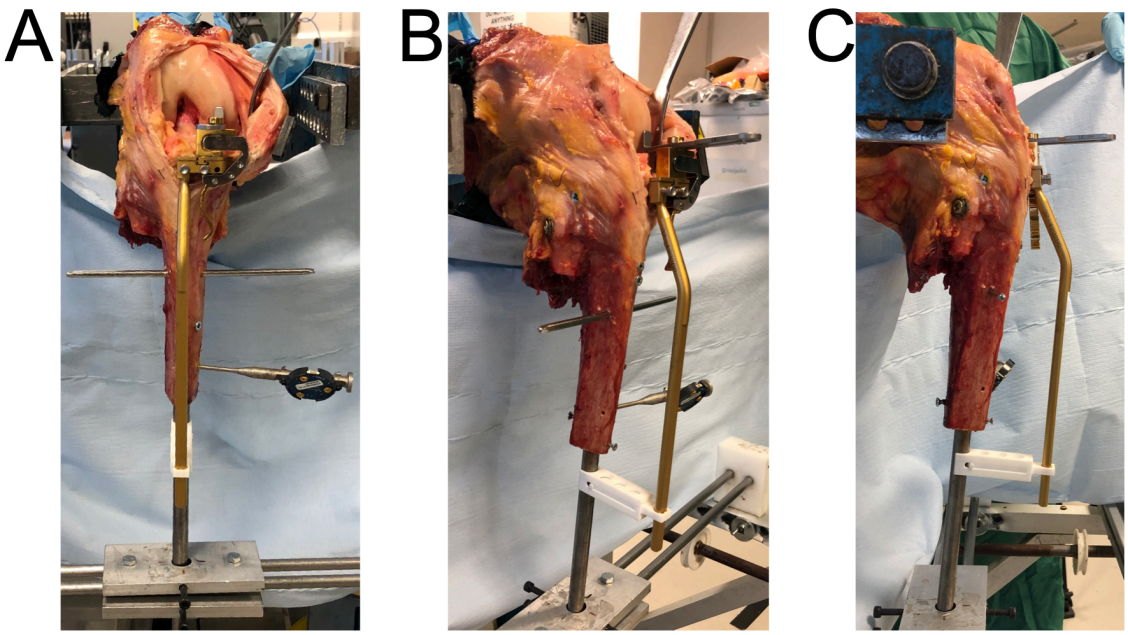


Figure 5.11. Cadaveric knee mounted on kinematics rig, with Oxford® Partial Knee system Microplasty® tibial cutting jig pinned to the proximal tibia and aligned to the tibial intramedullary rod using a bespoke 3D printed device. A: anterior view, B: Oblique view, C: Lateral view.

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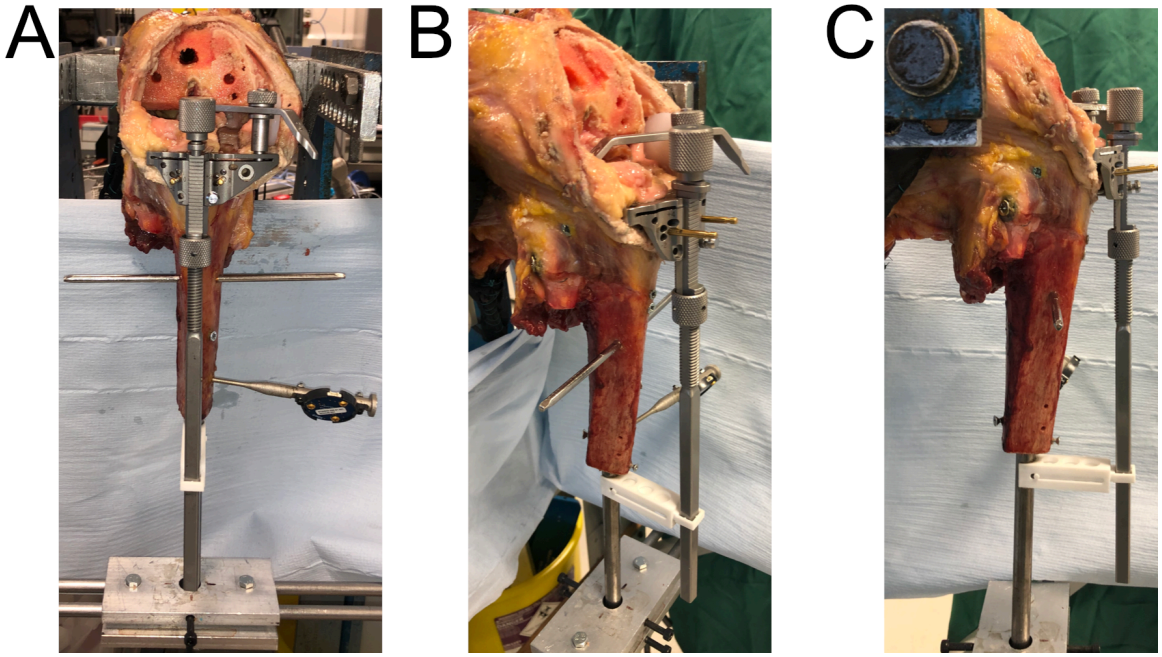


Figure 5.12. Cadaveric knee mounted on kinematics rig, with NexGen tibial cutting jig pinned to the proximal tibia and aligned to the tibial intramedullary rod using a bespoke 3D printed device. A: anterior view, B: Oblique view, C: Lateral view.

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5.2.2.4 *Implant Sequence*

A power calculation was undertaken, based on 3mm mean change in anterior-posterior tibial translation between the native state and TKA[353], which resolved that eight specimens were required to reach significance in anterior-posterior tibial translation (80% power, 95% confidence, significance p=0.05). Twenty-four specimens were tested, in three groups of eight, to assess the different implant (Figure 5.13). Group one was tested in the native state, then UKA-M, then BCA-M then TKA. Group two was tested in the native state, then UKA-L, BCA-L then TKA and Group three: native, Bi-UKA then TKA.

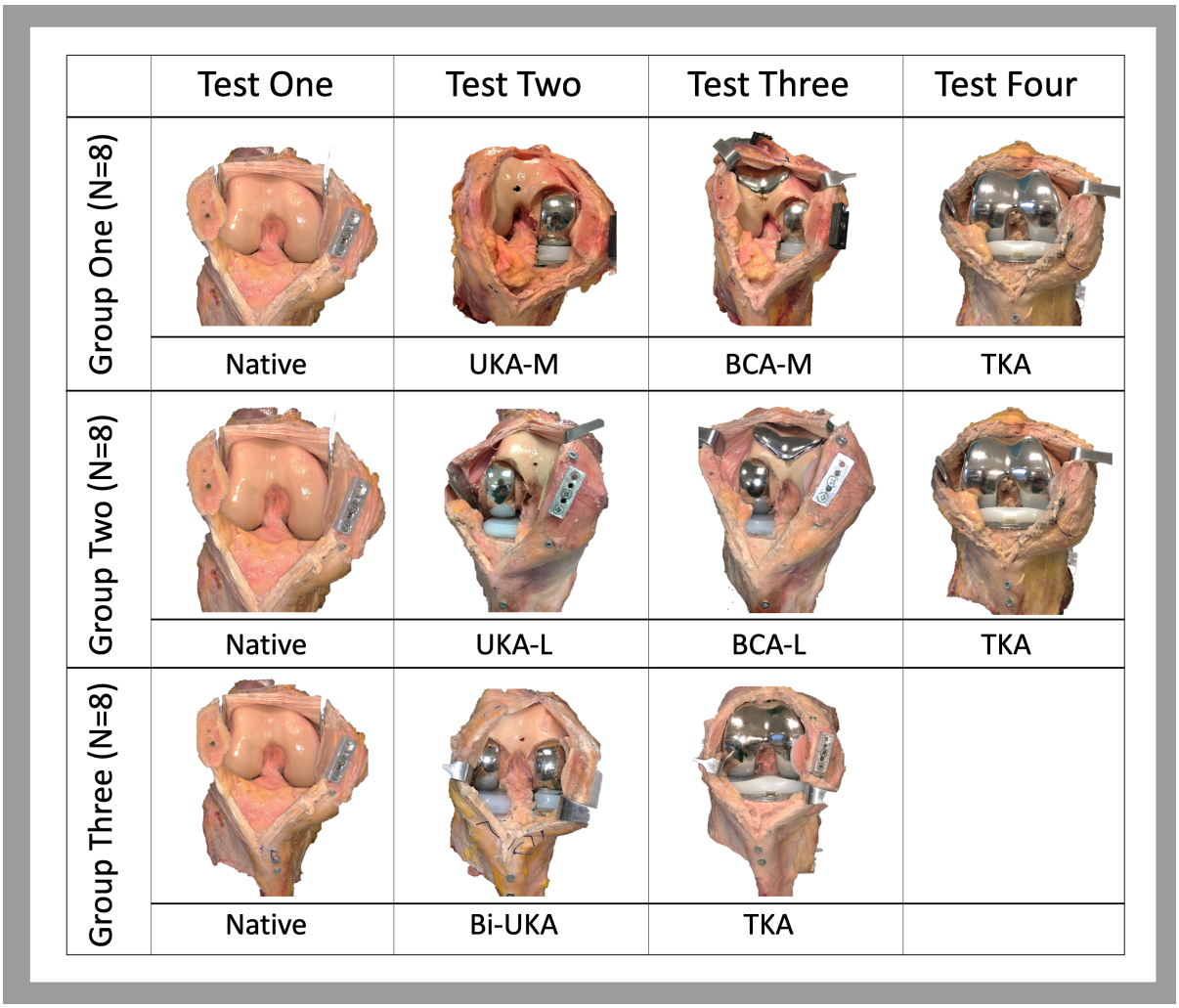


Figure 5.13. Cadaveric Specimens in testing groups showing the order of arthroplasty implantation. Medial Unicompartmental Arthroplasty (UKA-M), Lateral Unicompartmental Arthroplasty (UKA-L), Medial Bicompartmental Arthroplasty (BCA-M), Lateral Unicompartmental Arthroplasty (UKA-L). Bi-Unicondylar Arthroplasty (Bi-UKA), Posterior Cruciate-Retaining Total Knee Arthroplasty (TKA).

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Upon removal of PKA implants, some of the landmarks routinely used for alignment of the TKA cutting blocks were lost. To establish the distal femoral cut, the femoral intramedullary guide was positioned and pinned, with the femoral component of the UKA in situ. The UKA was then removed and the cutting block re-positioned over the pins. For the posterior femoral condyle cuts, the resected bone from the UKA was measured with callipers, and where possible, a shim was mounted on the referencing tool for the thickness of the resected bone + saw blade (Figure 5.15). On the tibial side, when converting a BCA to TKA, the depth gauge was referenced off of the native tibia, made possible by the fact the bone was free of wear (Figure 5.12). In the case of Bi-UKA conversion to TKA, following removal of the UKA tibial trays, only the ACL bone island remained (Figure 5.16). This island was resected through the slotted tibial cutting jig of the NexGen®, in line with the deeper tray, and the tibial cut freshened to create a uniform tibial platform (Figure 5.14).

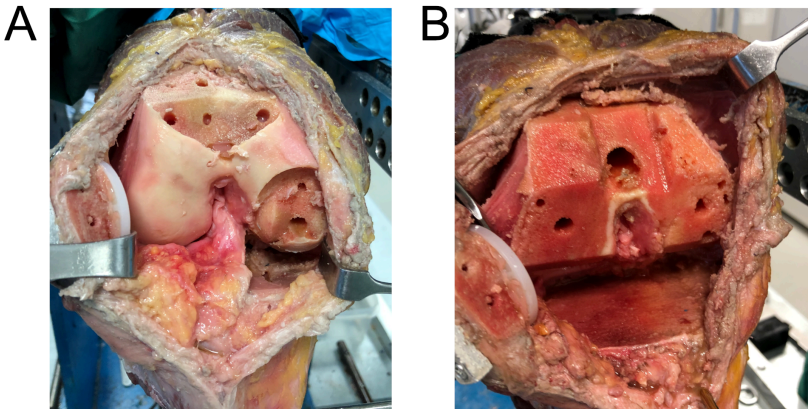


Figure 5.14. Remaining bone stock following removal of unicompartmental and patellofemoral arthroplasty implants (A) and preparation of bone surfaces for implantation of a standard primary total knee arthroplasty prosthesis (B).

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Figure 5.15. NexGen CR-Flex Total Knee Arthroplasty femoral referencing guide with 6mm shim to account for posterior condyle bone loss + saw blade width, following unicompartmental knee arthroplasty.

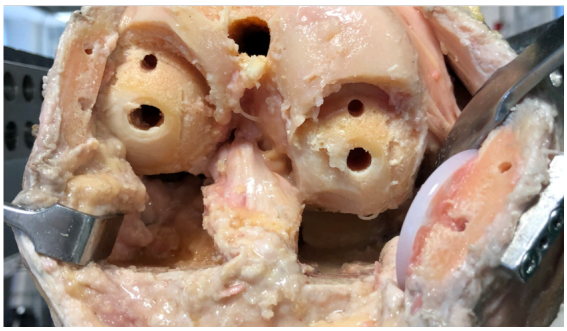


Figure 5.16. Cadaveric knee following removal of Bi-Unicondylar Arthroplasty prior to preparation of femur for Total Knee Arthroplasty, demonstrating the tibial 'bone island' with anterior cruciate ligament attachment.

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5.2.3 Pilot Testing

Three additional knees were used for pilot testing to determine that data collection would be possible, with particular attention paid to optical tracking. The experimental setup was tested to ensure it was capable of supporting the recreation of operating theatre conditions with the specimen mounted in the frame of the kinematics rig for the procedures, without compromising surgical technique, and support the sequential implantation of devices without compromising the soft-tissues, bone bed or injuring the ligaments. Finally, the order of implant testing was scrutinised to ensure it did not unfairly disadvantage TKA[355]. The three knees were tested first in the native state then after TKA with no intermediate PKA steps. The extension moment trajectories of these three 'TKA-only' knees fell within the 95% confidence interval of the whole sample. Further, repeated testing over 16 hours, including over-night refrigeration at 4°C, indicated that TKA was not disadvantaged by being last due to protocol length. Here, all subsequent TKA tests demonstrated similar extension moment and joint kinematic trajectories, in terms of both magnitude and shape, to those measured immediately after TKA (Figure 5.17). The extension moment trajectories of the three knees tested immediately after TKA (TKA-only) fell within the 95% confidence interval of the entire sample that included intermediary partial knee arthroplasty stages, providing confidence the protocol was valid and did not disadvantage TKA.

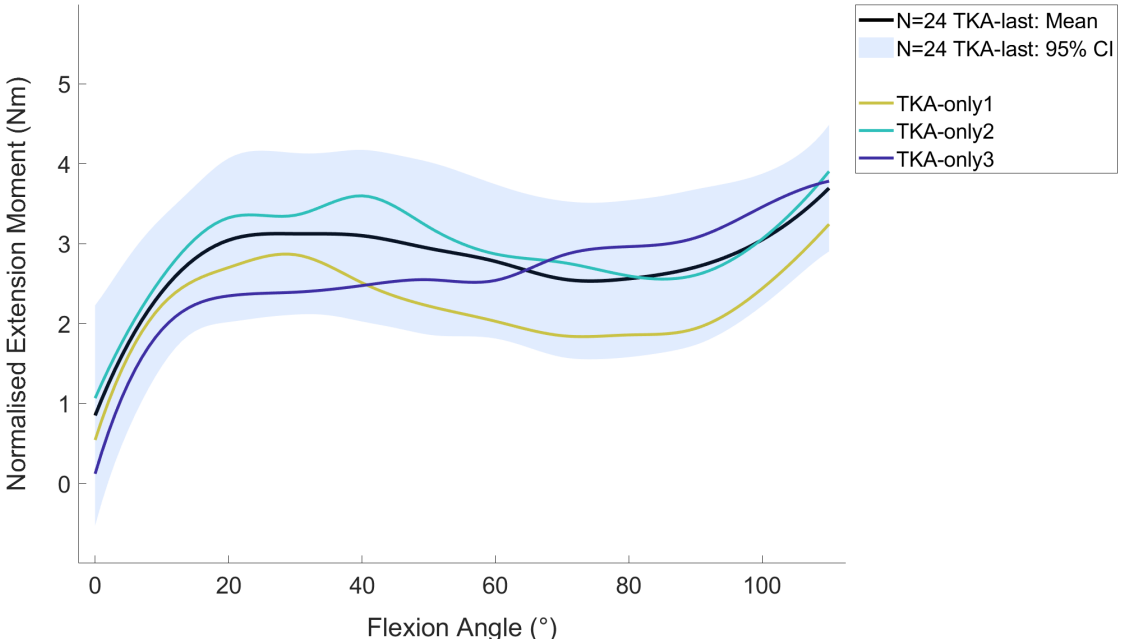


Figure 5.17. Normalised extension moment trajectories as the knee extended from 110 to 0 degrees flexion. The trajectories for the three TKA-only specimens (yellow, turquoise and purple lines) all fell within the 95% confidence interval for the mean for the twenty-four knees which had undergone combinations of PKA prior to TKA (TKA-last, black line with light blue 95% confidence interval).

Graph produced by Oliver Dandridge, and reproduced here from "Validity of repeated-measures analyses of in vitro arthroplasty kinematics and kinetics" Dandridge, O. Garner, A. Jeffers, J.R.T, Amis, A.A. Cobb, J.P. van Arkel, R.J. Journal of Biomechanics 2021 Aug 2;129:110669 with permission from Elsevier[355].

5.4 Anterior-Posterior Stability

5.4.1 Publication

This section includes text and images from the following publication, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Partial and Combined Partial Knee Arthroplasty: Greater Anterior-Posterior Stability Than Posterior Cruciate-Retaining Total Knee Arthroplasty. J Arthroplasty. 2021 Jun 29

5.4.2 Motivation and Hypothesis

Knee joint stability is intrinsically linked to function of the knee and outcomes for the patient. Instability leads to a significant change to the overall kinematics of the joint, disrupted soft-tissue balance and ligament tension. Loss of anterior-posterior stability can lead to difficulty with stair ascent / descent, hill walking and difficulty during sit-to-stand activities, fast walking, walking on uneven ground and the ability to rapidly change walking pace or direction. The consequences of a knee that 'gives way' may include falls, significant injury, loss of confidence, reduced independence and self-restricted participation in activities[69, 356]. Knee stability is the product of active and passive stabilisers of the joint, working synergistically. During single-leg standing, the knee must balance and support the weight of the body. Changes to the active and passive stabilisers of the knee disrupt the normal equilibrium across the joint and can lead to instability. Trauma or repeated micro-trauma, on the background of risk factors including advancing age, female sex, genetic predisposition, obesity or pre-existing misalignment, can trigger a series of events, both mechanical and biological, that ultimately result in disrupted joint architecture; sub-optimum function of the menisci or ligaments, or discord between the action of muscles acting across the joint. If arthrosis is asymmetrical, misalignment may become pathological and self-perpetuate the cycle of wear to the joint as a product of increased adduction moment in the varus knee, or abduction in the valgus knee[357].

PKA and CPKA preserve the ACL, but little is known of the impact of this on Anterior-Posterior Stability of the knee. We hypothesized that: 1) medial and lateral UKA would preserve the native stability of the knee 2) the addition of a patellofemoral arthroplasty would not compromise the stability associated with UKA, 3) Bi-UKA will affect both and anterior and posterior stability since the

medial and lateral tibial plateaux are resurfaced, 4) posterior-cruciate-retaining TKA would preserve posterior, but not passive anterior stability.

5.4.3 Kinematics Rig Design and Experimental Setup

A well-established kinematics rig was used for testing (Figure 5.19, Figure 5.20). The rig consists of a manually-operated rotating arm, capable of passively moving the knee through the flexion-extension cycle. The cadaveric knees were prepared as discussed in section 5.2.1. The potted femur was clamped to the mobile arm, with the centre of rotation aligned to the transepicondylar axis of the knee. In this position, the tibia hangs vertically below[358, 359]. The fabric bound tendons were loaded to 44 N in proportion to their cross-sectional area (Rectus femoris & vastus intermedius 1.2Kg; vastus lateralis longus 1.1Kg, vastus lateralis obliquus 0.3Kg, vastus medialis longus 0.5Kg, vastus medialis obliquus 0.3Kg, ITB 0.6Kg, medial hamstrings 0.2kg, lateral hamstrings 0.2Kg). This loading is similar to the resting loading across a knee joint (e.g. during sitting) and is applied to ensure the joint surfaces are in contact during the otherwise passive stability measurements, eliminating separation of the articular surfaces[360-362]

A Steinmann pin was drilled mediolaterally through the tibia, approximately 50mm distal to the joint line, perpendicular to the tibial shaft. Two semi-circular hoops were hung from the pin, one anterior, the other posterior with a cord attached, each passed over a pulley (Figure 5.18). Specimens were tested first with no load to either cord, then with a 90 N anterior load to simulate the anterior drawer (Figure 5.19) with a similar force to that of a KT 1000 arthrometer[363], then similarly via the posterior cord to create a posterior drawer (Figure 5.20), without imposing a rotational torque.

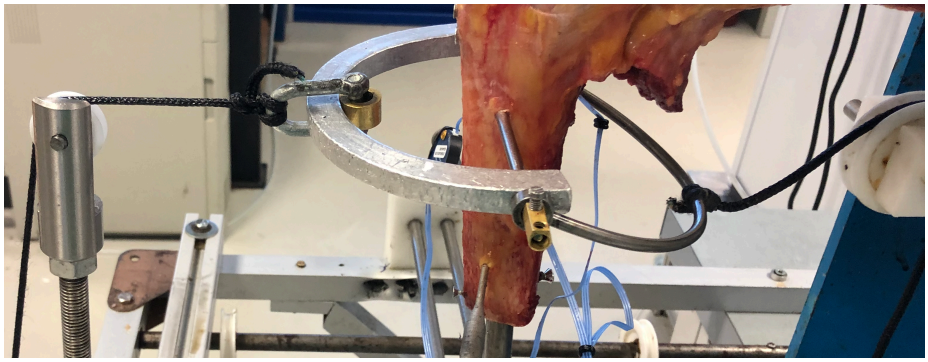


Figure 5.18. Anterior and Posterior Hoops hooked over a medio-lateral tibial Steinmann Pin, Each connected to cords draped over pulleys. Here shown with an anterior 90 N load.

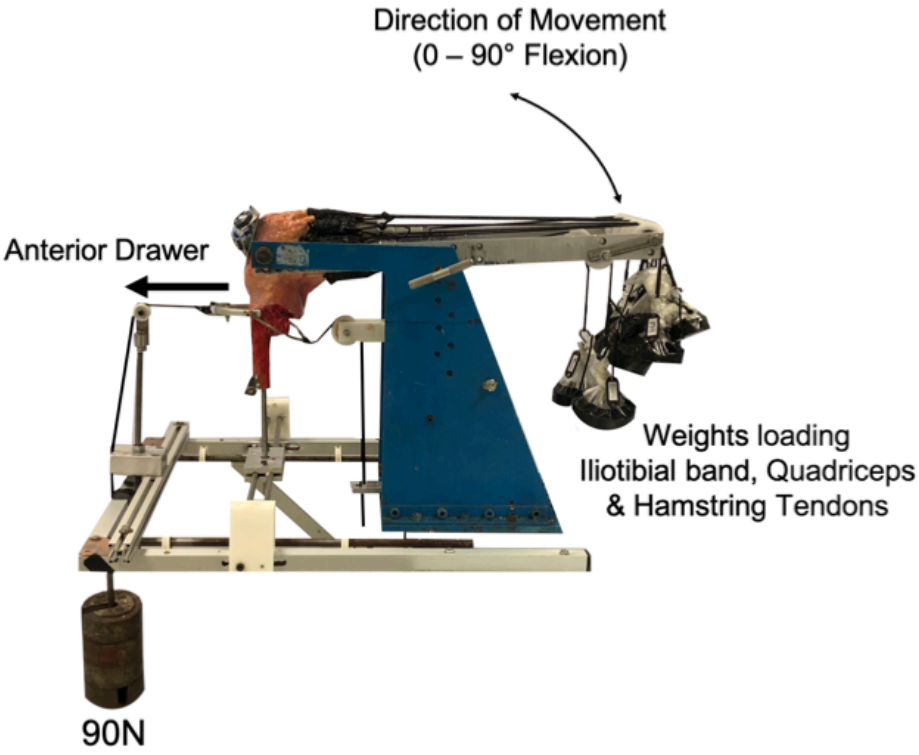


Figure 5.19. Kinematics Rig: Side view, with cadaveric knee mounted, subject to Quadriceps, Iliotibial Band and Hamstring Tendon Loading and 90 Newtons Anterior Drawer on the Tibia.

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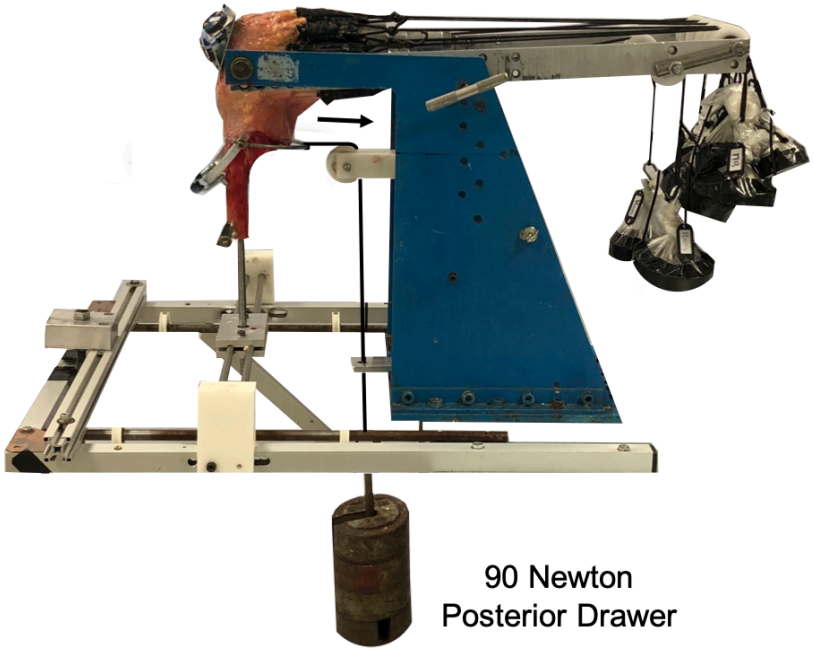


Figure 5.20. Kinematics Rig: Side view, with cadaveric knee mounted, subject to Quadriceps, Iliotibial Band and Hamstring Tendon Loading and 90 Newtons Posterior Drawer on the Tibia.

The tibial intramedullary rod passes through a block, mounted to the front of the rig. The block prevents the tibia from deviating in the sagittal plane under the force of quadriceps loading, as the knee is flexed and extended, but runs freely on rails in the coronal plane so as not to restrict varus / valgus deviation of the knee during motion. The hole in the centre of the block is sufficiently large to allow the IM rod to rotate freely within it, reflecting internal and external rotation of the tibia (Figure 5.21).

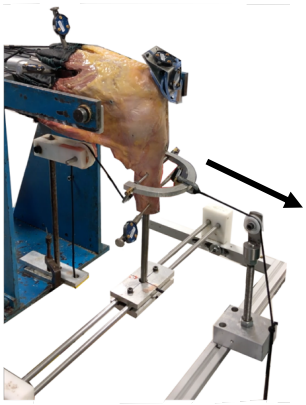


Figure 5.21. Kinematics Rig: Antero-Lateral view with cadaveric knee at 90 degrees of flexion, subject to 90 Newton Anterior Drawer.

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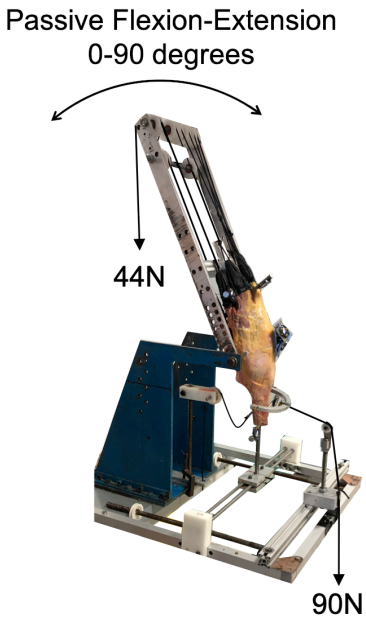


Figure 5.22. Kinematics Rig Mounted with a Cadaveric Knee, subject to Quadriceps, Iliotibial Band and Hamstring Loading, and 90 Newtons Anterior Tibial Drawer. Here shown towards full extension.

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The rig operator manually lifted the arm of the rig, flexing and extending the knee (Figure 5.22). Each flexion-extension cycle took approximately four seconds to complete, repeated five times per implant state and per drawer load applied (90 N anterior, neutral and 90 N posterior) whilst the motion was continuously tracked.

5.4.4 Specimens

A power calculation was undertaken, which resolved that eight specimens would be sufficient to detect 3.5 ± 3mm mean change in anterior-posterior tibial translation between the native state and TKA[364] with 80% power and 95% confidence.

The demographics of the cadaver donors used in this series are shown in Table 5.1

Group	Age (Years)	Body Mass Index (Kg/m2)	Sex (M:F)	Laterality (Right : Left)	Test 1	Test 2	Test 3	Test 4
One	66± 5.8	24.9 ± 4.0	5 : 3	8 : 0	Native	UKA-M	BCA-M	TKA
Two	67± 5.3	23.2 ± 4.1	4 : 4	0 : 8	Native	UKA-L	BCA-L	TKA
Three	63 ± 2	24.3 ± 3.9	4 : 4	4 : 4	Native	Bi-UKA	TKA	

Table 5.1. Demographics of cadaveric testing groups. Values are shown as means with standard deviation. Medial Unicompartmental Arthroplasty (UKA-M), Lateral Unicompartmental Arthroplasty (UKA-L), Medial Bicompartmental Arthroplasty (BCA-M), Lateral Unicompartmental Arthroplasty (UKA-L). Bi-Unicondylar Arthroplasty (Bi-UKA), Total Knee Arthroplasty (TKA). Age refers to the average age of the donor at death.

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5.4.5 Data and Statistical Analysis

Knee translations/rotations were calculated from the optically tracked positional data using a customised MATLAB script (Version 9.5, MathWorks) adopting a well-established coordinate system[365]. Anterior laxity was calculated from the anterior tibial translation data by subtracting the neutral load case data from the 90 N anterior drawer data. Similarly, posterior laxity was calculated by subtracting the neutral data from the 90 N posterior drawer data. When combined, these gave overall A-P laxity (the range of anterior-posterior tibial translation) under 90 N anterior/posterior drawer. For a typical flexion/extension cycle, the optical tracking system recorded 400 data points.

To enable statistical analyses, these data were sampled at 10° flexion increments from 0° to 90° flexion.

For each native knee/arthroplasty state, the A-P laxity data were averaged over the complete range of knee flexion, thus collapsing all changes in anterior/posterior tibial translation into an "overall" value for each state (reported with ± standard deviation). The overall laxities for each arthroplasty state were compared to each other and to the native knee by calculating percentage change and Mean Absolute (MA) difference. This MA difference metric mitigates any possible cancelling effects of positive and negative differences. Further, the change in overall laxity (that is: the sum of anterior plus posterior laxities) for the complete set (N = 24) between native and TKA was analysed.

Statistical analyses were then performed to identify whether laxity increases were due to increased anterior tibial translation, posterior tibial translation, or both, and whether differences were isolated to specific angles of knee flexion, or were apparent across the entire range of knee flexion. Intra-state measures of tibial translation were tested using the Shapiro-Wilk test and found to be normally distributed. Data were analysed with a two-way repeated measures analysis of variance in SPSS (version 27; IBM). The dependent variable was the change in tibial translation when subjected to 90N anterior or posterior drawer and the independent variables were implantation state (native, partial knee arthroplasty, TKA) and flexion angle (0-90° in 10° increments). Anterior and posterior tibial translation data were analysed separately resulting in six analyses (both directions, for each of the three knee sets: medial, lateral and bi-unicondylar). Post hoc paired t tests with Bonferroni correction were applied when differences across tests (as indicated by the 95% confidence interval) were found. Adjusted p values, multiplied in SPSS by the appropriate Bonferroni correction factor and capped at a maximum value of 1, were reported.

5.5 Results

The overall laxity of the complete set of native knees (n=24) was 6.3 $\pm$ 1.8mmn: the medial partial knee arthroplasty set exhibited a native laxity of 6.4 $\pm$ 1.6mm, whilst the lateral partial knee arthroplasty set had a mean laity of 7.0 $\pm$ 1.4mm (Table 5.2, Figure 5.23).

Partial Knee Arthroplasty Set	Implant State	Mean overall Laxity (mm)	Mean Absolute Difference to Native (mm)
Medial PKA	Native	6.4 ± 1.6	
	UKA-M	6.0 ± 2.5	1.0
	BCA-M	6.0 ± 2.6	1.5
	TKA	20.4 ± 7.5	14.0
Lateral PKA	Native	7.0 ± 1.4	
	UKA-L	7.7 ± 1.6	1.2
	BCA-L	7.2 ± 1.9	0.8
	TKA	20.6 ± 5.0	13.7
Bi-UKA	Native	5.5 ± 2.2	
	Bi-UKA	10.6 ± 5.9	5.2
	TKA	20.8 ± 5.7	15.3
Complete Set	Native (N=24)	6.3 ± 1.8	
	TKA (N=24)	20.6 ± 5.9	14.3

Table 5.2. The overall laxity of the native and arthroplasty-implanted knee (A-P laxity averaged across the flexion range) with Mean Absolute (MA) differences relative to the native knee.

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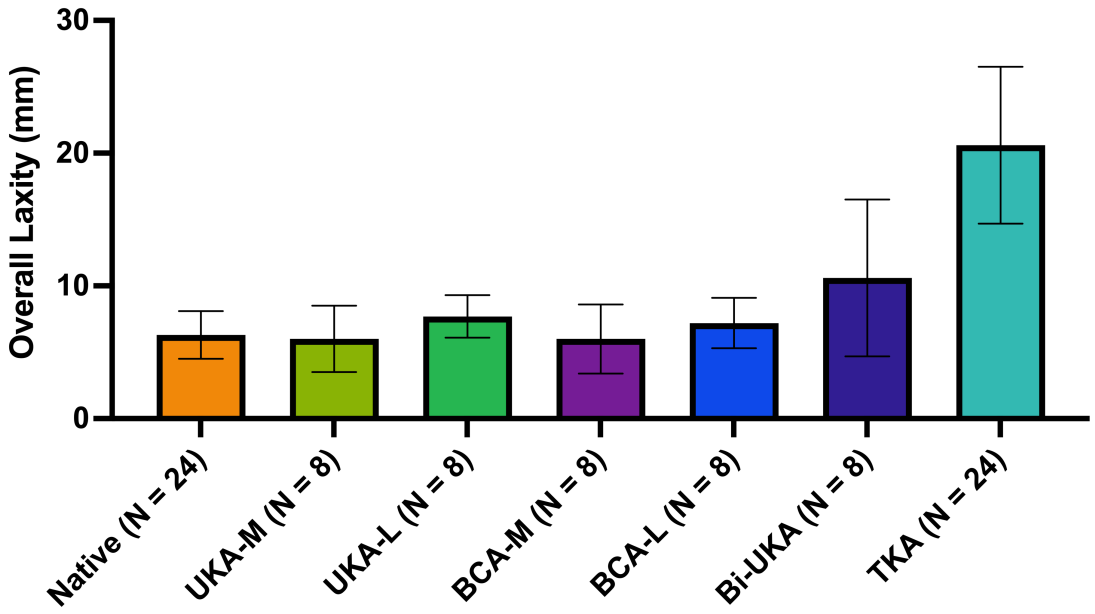


Figure 5.23. Overall anterior-posterior laxity (averaged across all flexion angles) with standard deviation for each implant state.

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Laxity is defined as the sum of anterior tibial translation plus the positive value of posterior translation in millimetres. The mean overall laxity at each flexion angle is seen in Figure 5.24 and detailed in Table 5.3.

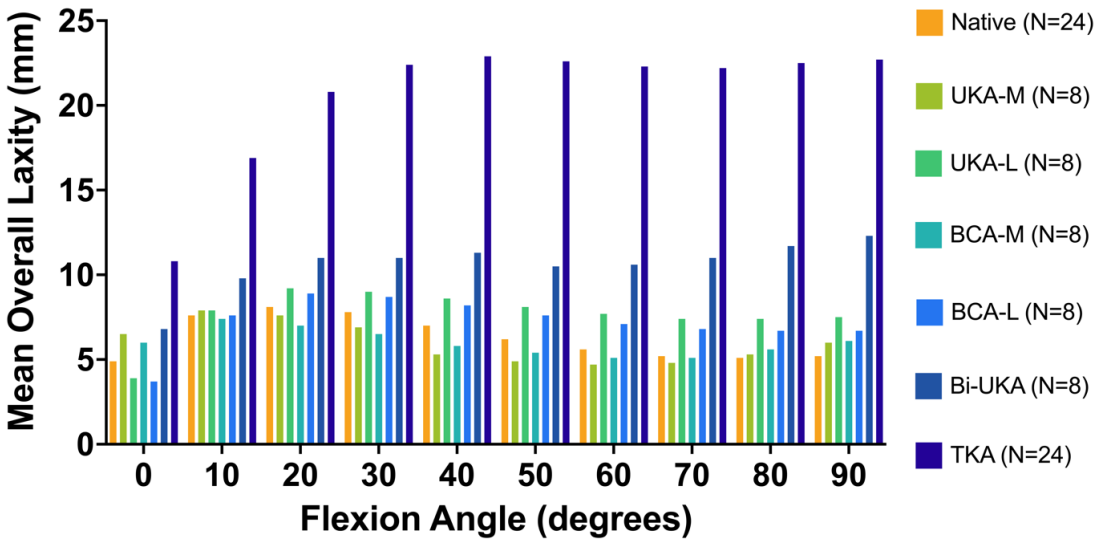


Figure 5.24. Mean overall laxity (the sum of anterior plus posterior laxities) in millimetres by flexion angle for the native knee, medial unicompartmental arthroplasty (UKA-M), lateral unicompartmental arthroplasty (UKA-L), medial bicompartmental arthroplasty (BCA-M), lateral bicompartmental arthroplasty (BCA-L), bi-unicondylar arthroplasty (Bi-UKA) and total knee arthroplasty (TKA).

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Flexion Angle (degrees)	Native (N=24)	UKA-M (N=8)	UKA-L (N=8)	BCA-M (N=8)	BCA-L (N=8)	Bi-UKA (N=8)	TKA (N=24)
0	4.9 ± 1.9	6.5 ± 1.8	3.9 ± 1.3	6.0 ± 1.3	3.7 ± 2.0	6.8 ± 4.5	10.8 ± 5.2
10	7.6 ± 1.9	7.9 ± 1.9	7.9 ± 1.9	7.4 ± 2.1	7.6 ± 1.5	9.8 ± 5.2	16.9 ± 5.7
20	8.1 ± 1.8	7.6 ± 2.2	9.2 ± 1.8	7.0 ± 2.7	8.9 ± 1.9	11.0 ± 6.1	20.8 ± 5.8
30	7.8 ± 1.8	6.9 ± 2.3	9.0 ± 1.9	6.5 ± 3.0	8.7 ± 2.1	11.0 ± 6.9	22.4 ± 5.8
40	7.0 ± 2.0	5.3 ± 3.4	8.6 ± 2.1	5.8 ± 3.0	8.2 ± 2.2	11.3 ± 7.2	22.9 ± 6.0
50	6.2 ± 2.0	4.9 ± 3.4	8.1 ± 2.0	5.4 ± 3.0	7.6 ± 2.3	10.5 ± 7.2	22.6 ± 6.4
60	5.6 ± 2.1	4.7 ± 3.5	7.7 ± 2.0	5.1 ± 3.0	7.1 ± 2.3	10.6 ± 6.8	22.3 ± 6.8
70	5.2 ± 2.0	4.8 ± 3.5	7.4 ± 2.0	5.1 ± 3.0	6.8 ± 2.4	11.0 ± 6.5	22.2 ± 7.2
80	5.1 ± 2.1	5.3 ± 3.5	7.4 ± 1.9	5.6 ± 3.2	6.7 ± 2.4	11.7 ± 6.3	22.5 ± 7.8
90	5.2 ± 2.3	6.0 ± 3.8	7.5 ± 2.1	6.1 ± 3.7	6.7 ± 2.6	12.3 ± 6.0	22.7 ± 8.2

Table 5.3. Implant state anterior-posterior laxity per flexion angle. All figures are means with standard deviation in milimetres

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The effect of UKA.

Following UKA, the recorded changes in laxity did not reach significance (UKA-M 6.0 ± 2.6mm, UKA-L 7.7 ± 1.6, arithmetic mean differences ≤ 1 mm, p = 1, Figure 5.25 A and B, Table 5.4 and Table 5.5).

The effect of BCA

BCA-M laxity was 6.0 ± 2.6mm, whilst BCA-L overall laxity was 7.2 ± 1.9mm (Table 5.2, Figure 5.23). This was reflected in the statistical analyses: no differences were identified between BCA-M or BCA-L and the native knee (all arithmetic mean anterior/posterior tibial translation differences ≤ 1 mm, p ≥ 0.199, Table 5.4, Table 5.5). Conversion of UKA to BCA made little difference to the laxity: UKA-M to BCA-M MA difference 1.3mm, UKA-L to BCA-L MA difference 1.4mm (all arithmetic mean anterior-posterior tibial translation differences ≤ 1 mm, p ≥ 0.448, Figure 5.25 A, Table 5.4 and Table 5.5).

The effect of Bi-UKA

In the Bi-UKA set, the native knees had a mean overall laxity of 5.5 ± 2.2 mm, which increased by 93% to 10.6 ± 5.9mm following Bi-UKA (Table 5.2, Figure 5.23). Statistical analysis revealed that the effect of Bi-UKA on anterior tibial translation depended on the angle of knee flexion (p = 0.001): the arithmetic mean difference compared to the native knee varied from 2 mm at 0° flexion (p = 0.402) to 8 mm at 90° (p = 0.011; Figure 5.25C and Table 5.6). Conversely, Bi-UKA was not found to affect posterior tibial translation across all flexion angles tested (arithmetic mean difference 0 mm, p=1, Figure 5.25C and Table 5.6).

The effect of TKA

Overall laxity of the complete set (n=24) increased from native 6.3 ± 1.8mm to 20.6 ± 5.9mm following TKA, an increase of 228% (Table 5.2, Figure 5.23). More specifically, for group one, the medial partial knee arthroplasty set (Figure 5.25A), TKA overall laxity was 20.4 ± 7.5mm (Table 5.2). Anterior tibial translation increased by 6-15 mm, following TKA when the knee was flexed (p ≤ 0.041 between 10-80°, and p = 0.066 at 90°, Table 5.4). The largest increases in anterior tibial translation compared to the native knee occurred across the mid-range of knee flexion: 30°-60° (arithmetic mean differences ≥13mm, p≤ 0.005).

For group two, the lateral partial knee arthroplasty set (Figure 5.25B), TKA resulted in an 196% increase in overall laxity from native 7.0 ± 1.4mm to TKA 20.6 ± 5.0mm. Anterior tibial translation increased by 8-9 mm when compared to the native knee, UKA-L and BCA-L (all $p \leq 0.037$, Figure 5.25B).

For group three, the Bi-UKA set (Figure 5.25C), overall laxity increased 279% from native 5.5mm ± 2.2mm to 20.8 ± 5.7mm following TKA (Table 5.2). Anterior tibial translation increased by 5-18 mm compared to the native knee, at any angle of knee flexion ($p \leq 0.039$ at 0-10° and 30-90°, $p=0.066$ at 20°, Table 5.6). This was also true when comparing TKA to Bi-UKA, with 4-11 mm increased anterior translation measured when the knee was flexed ($p \leq 0.024$ at 10° and from 30-90°, $p = 0.079$ at 20°, Table 5.6).

For all three groups, TKA posterior tibial translation was 3-4 mm greater across all flexion angles when compared to the native knee, BCA-M, BCA-L and Bi-UKA ($p \leq 0.041$, Figure 5.25, Table 5.4, Table 5.6)

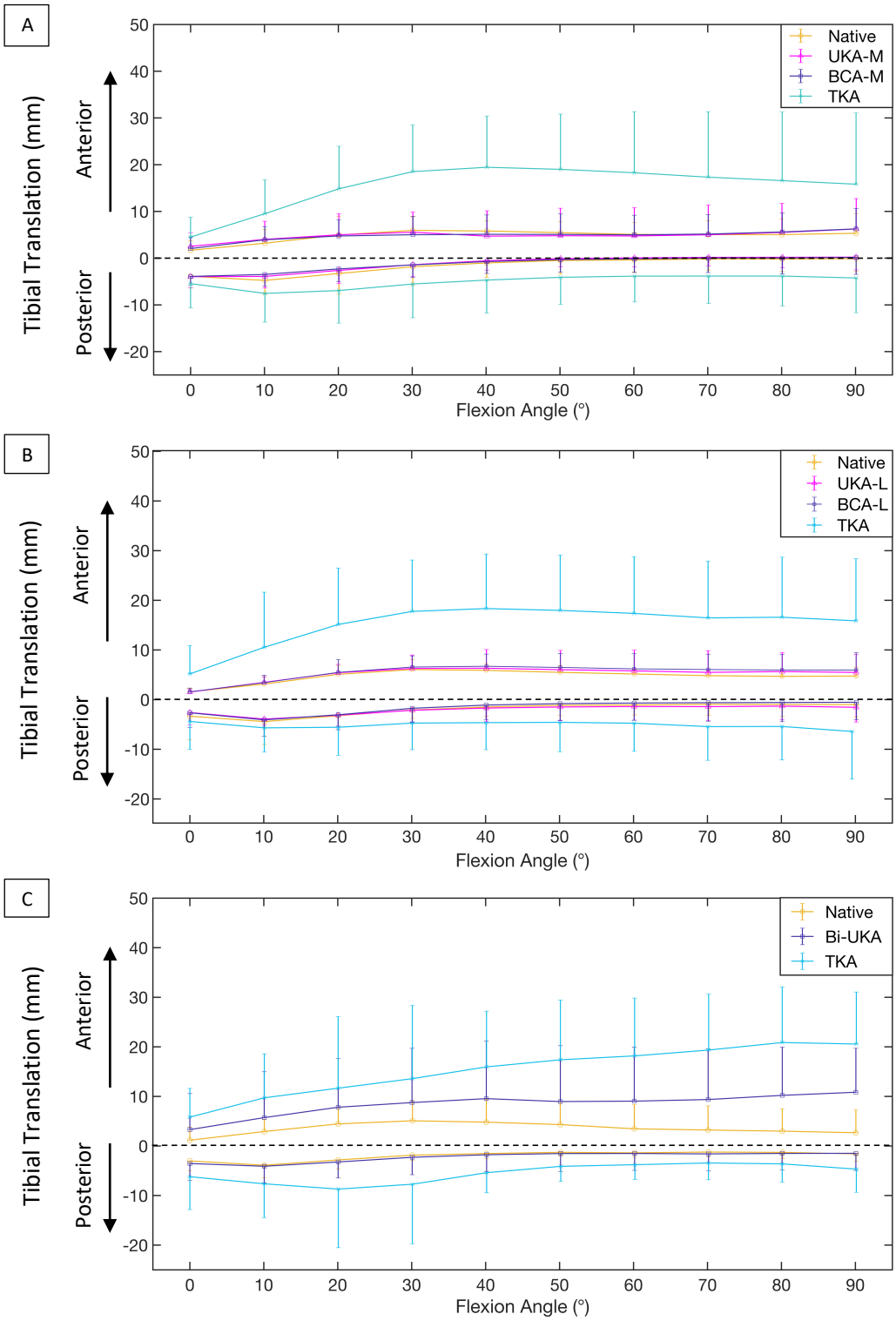


Figure 5.25. Anterior-posterior laxity envelopes: A. native knee, medial unicompartmental arthroplasty (UKA-M), medial bicompartmental arthroplasty (BCA-M) and total knee arthroplasty (TKA). B. native knee, Lateral Unicompartmental Arthroplasty (UKA-L), Lateral Bicompartmental Arthroplasty (BCA-L) and TKA and C. native knee, Bi-Unicondylar Arthroplasty (Bi-UKA) and TKA[§].

[§]For each state, the upper line is equal to the change in anterior tibial translation when 90 N anterior drawer is applied, and the lower line is equal to the change in posterior tibial translation under 90 N posterior drawer (Mean ± Standard deviation; n = 8 knees for each set). The further the lines are apart, the greater the A-P knee laxity for that state at that flexion angle, indicating decreased A-P stability.

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	Direction	Flexion *(deg)*	Comparison with native			Comparison between arthroplasties		
			Arthroplasty	Difference† *(mm)*	P Value‡	Comparison	Difference† *(mm)*	P Value‡
Group One, Medial Partial Knee Arthroplasty Set	Anterior	0	UKA-M	1 ± 2	1.000	BCA-M = UKA-M	0 ± 1	0.448
			BCA-M	0 ± 2	1.000	TKA > UKA-M	2 ± 3	0.421
			TKA	3 ± 4	0.163	TKA > BCA-M	2 ± 3	0.106
		10	UKA-M	1 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	1 ± 3	1.000	TKA > UKA-M	6 ± 5	0.041*
			TKA	6 ± 5	0.013*	TKA > BCA-M	6 ± 5	0.029*
		20	UKA-M	0 ± 4	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	0 ± 4	1.000	TKA > UKA-M	10 ± 6	0.005*
			TKA	10 ± 6	0.002*	TKA > BCA-M	10 ± 7	0.005*
		30	UKA-M	0 ± 3	1.000	UKA-M > BCA-M	1 ± 2	1.000
			BCA-M	-1 ± 3	1.000	TKA > UKA-M	13 ± 7	0.002*
			TKA	13 ± 7	0.002*	TKA > BCA-M	13 ± 7	0.001*
		40	UKA-M	-1 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	-1 ± 2	1.000	TKA > UKA-M	15 ± 8	0.002*
			TKA	14 ± 8	0.002*	TKA > BCA-M	14 ± 7	0.001*
		50	UKA-M	-1 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	0 ± 2	1.000	TKA > UKA-M	14 ± 8	0.003*
			TKA	14 ± 8	0.004*	TKA > BCA-M	14 ± 8	0.002*
		60	UKA-M	0 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	0 ± 2	1.000	TKA > UKA-M	14 ± 9	0.006*
			TKA	13 ± 9	0.007*	TKA > BCA-M	13 ± 9	0.005*
		70	UKA-M	0 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	0 ± 1	1.000	TKA > UKA-M	12 ± 10	0.016*
			TKA	12 ± 10	0.016*	TKA > BCA-M	12 ± 9	0.014*
		80	UKA-M	0 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	1 ± 1	1.000	TKA > UKA-M	11 ± 10	0.028*
			TKA	12 ± 10	0.025*	TKA > BCA-M	11 ± 10	0.027*
		90°	UKA-M	1 ± 3	1.000	BCA-M = UKA-M	0 ± 2	1.000
			BCA-M	1 ± 1	0.199	TKA > UKA-M	10 ± 10	0.066
			TKA	11 ± 11	0.05	TKA > BCA-M	10 ± 10	0.057
	Posterior	All	UKA-M	0 ± 1	1.000	BCA-M = UKA-M	0 ± 2	1.000
		All	BCA-M	0 ± 1	1.000	TKA > UKA-M	4 ± 4	0.069
		All	TKA	3 ± 3	0.041*	TKA > BCA-M	4 ± 3	0.017*

§An interaction between flexion angle and implant was detected under anterior tibial drawer (p = 0.001), but not posterior drawer (p = 0.142 posterior). Under posterior drawer there was an effect of arthroplasty across all flexion angles (p=0.004). For comparisons with intact, positive values indicate increased translation was measured after arthroplasty. For comparisons between arthroplasties, the greater than symbol (>) indicates which arthroplasty had the greater translation. †The values are given as the mean and the 95% confidence interval. ‡T test with Bonferroni Correction. *The difference was significant (p < 0.05).

Table 5.4. Mean Change in Translation for Group One, the Medial Partial Knee Arthroplasty Set[§].

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Group Two, Lateral Partial Knee Arthroplasty Set	Direction	Comparison with native			Comparison between arthroplasties		
		Arthroplasty	Difference† *(mm)*	P Value‡	Comparison	Difference† *(mm)*	P Value‡
	Anterior	UKA-L	0 ± 2	1.000	BCA-L = UKA-L	0 ± 1	1.000
		BCA-L	1 ± 1	1.000	TKA > UKA-L	9 ± 8	0.037*
		TKA	9 ± 8	0.026*	TKA > BCA-L	8 ± 7	0.025*
	Posterior	UKA-L	0 ± 2	1.000	UKA-L > BCA-L	1 ± 2	1.000
		BCA-L	0 ± 1	1.000	TKA > UKA-L	4 ± 6	0.221
		TKA	5 ± 7	0.243	TKA > BCA-L	5 ± 7	0.215

§Data are given for all flexion angles (main effect). No interactions were detected (p = 0.240 anterior, p = 0.089 posterior); rather, there was an effect of arthroplasty across all flexion angles (p ≤ 0.034). For comparisons with intact, positive values indicate increased translation was measured after arthroplasty. For comparisons between arthroplasties, the greater than symbol (>) indicates which arthroplasty had the greater translation. †The values are given as the mean and the 95% confidence interval. ‡T test with Bonferroni Correction. *The difference was significant (p < 0.05).

Table 5.5. The Mean Change in Translation for Group Two, the Lateral Partial Knee Arthroplasty Set§.

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Group Three, Bi-Unicondylar Knee Set	Direction	Flexion *(deg)*	Comparison with native			Comparison between arthroplasties		
			Arthroplasty	Difference† *(mm)*	P Value‡	Comparison	Difference† *(mm)*	P Value‡
	Anterior	0	Bi-UKA	2 ± 4	0.402	TKA > Bi-UKA	3 ± 3	0.166
			TKA	5 ± 3	0.002*			
		10	Bi-UKA	3 ± 5	0.383	TKA > Bi-UKA	4 ± 3	0.017*
			TKA	7 ± 4	0.006*			
		20	Bi-UKA	3 ± 6	0.327	TKA > Bi-UKA	4 ± 4	0.079
			TKA	7 ± 8	0.066			
		30	Bi-UKA	4 ± 7	0.407	TKA > Bi-UKA	5 ± 4	0.024*
			TKA	8 ± 8	0.039*			
		40	Bi-UKA	5 ± 7	0.243	TKA > Bi-UKA	6 ± 5	0.01*
			TKA	11 ± 7	0.004*			
		50	Bi-UKA	5 ± 7	0.236	TKA > Bi-UKA	8 ± 7	0.017*
			TKA	13 ± 7	0.003*			
		60	Bi-UKA	6 ± 7	0.103	TKA > Bi-UKA	9 ± 6	0.008*
			TKA	15 ± 7	0.001*			
		70	Bi-UKA	6 ± 6	0.053	TKA > Bi-UKA	10 ± 6	0.003*
			TKA	16 ± 7	0.001*			
		80	Bi-UKA	7 ± 6	0.023*	TKA > Bi-UKA	11 ± 6	0.003*
			TKA	18 ± 7	<0.001*			
		90°	Bi-UKA	8 ± 6	0.011*	TKA > Bi-UKA	10 ± 5	0.001*
			TKA	18 ± 6	<0.001*			
	Posterior	All	Bi-UKA	0 ± 2	1.000	TKA > Bi-UKA	3 ± 2	0.012*
		All	TKA	4 ± 2	0.001*			

§An interaction between flexion angle and implant was detected under anterior tibial translation drawer (p = 0.001), but not posterior drawer (p = 0.321). For posterior tibial translation drawer there was an effect of arthroplasty across all flexion angles (p < 0.001). For comparisons with intact, positive values indicate increased translation was measured after arthroplasty. For comparisons between arthroplasties, the greater than symbol (>) indicates which arthroplasty had the greater translation. †The values are given as the mean and the 95% confidence interval. ‡T test with Bonferroni Correction. *The difference was significant (p < 0.05).

Table 5.6.The Mean Change in Translation for Group Three, the Bi-unicondylar Knee Set§

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5.6 Discussion

The most important finding of this study is the clear contrast between the large increases of A-P translation laxity post-TKA, versus the small changes caused by the UKA , BCA and Bi-UKA, rejecting the null hypothesis. The data suggest that knee A-P translational laxity remains near-normal as long as the primary restraints of the cruciates and either one of the secondary meniscal restraints remain intact, as is the case for UKA and BCA. The presence of a functioning ACL and either meniscus allow near normal laxity to be retained throughout the range of motion, while their absence has a measurable impact. Anterior tibial translation increased following Bi-UKA at high (80-90°) flexion angles even though the ACL was present. There is good evidence that the medial meniscus is a secondary stabiliser of A-P laxity[30, 366] but the role of the lateral meniscus is harder to discern, as a consequence of its increased mobility, even when the ACL is absent[31]. Loss of posterior joint height in the Bi-UKA, for example as a consequence of increased tibial downslope, may explain the observed findings, as this would likely increase tibial anterior translation[367].

Instability following TKA is recognised as a significant risk factor for revision surgery[368]. The ACL is the primary passive anterior stabiliser of the knee that also has a significant role in proprioception[369]. The loss of the ACL and both menisci in this study resulted in significant increases in anterior tibial translation following TKA, corroborating the findings of others[353]. Notably, TKA exhibited the greatest increase in laxity in mid-flexion. Mid-flexion instability has been commonly reported both in vivo and in vitro[370]. These observations raise the question of how much increase in laxity is significant for the patient? There has been little objective data, but Sculco suggested that an increase of A-P laxity greater than 7 to 10 mm could indicate moving to a constrained-condylar design [371].

The majority of patients with end-stage osteoarthritis have an intact ACL: in one series, ACL integrity was assessed prior to resection at the time of TKA surgery and revealed that 78% of cases sacrificed an intact, functional ACL, as part of the standard TKA procedure[64, 65]. Another study of 300 consecutive patients undergoing TKA for Kellgren-Lawrence grade ≥ 3, revealed that the ACL was intact in 55% patients, frayed in 27%, and disrupted or absent in the remaining[66]. There is an inherent risk with implantation of any arthroplasty device where outcome is linked to the function of the ACL, since its physical presence does not automatically equate to good function. A number of studies have demonstrated that histological changes are seen in the majority of ACLs in OA knees[372, 373], though this is not necessarily a contraindication to ligament retention. Myxoid degeneration is

the most common histopathological finding (63%), the incidence of which increases with age and OA severity[374].

Small increases in posterior tibial translation were also observed in the TKA state, in line with the findings of others[353, 375]. During each experiment, the PCL was visually inspected through the wound, at the time of TKA implantation, and no macroscopic structural damage was seen. With any CR-TKA there is a risk of avulsion of the tibial attachment of the PCL that is not visible through the anterior window, leaving the PCL as a space-filler within the knee, but not a functioning restraint[376-379]. Therefore, a digital examination of the PCL was also undertaken to assess tension which, in each case was felt to be appropriate with no obvious damage sustained. This work shows that there is no significant increased laxity associated with UKA of either the medial or lateral tibiofemoral compartments, and that the lateral procedure in particular is able to preserve native A-P laxity, despite the well-described increased rotational movement and femoral roll-back in the lateral compartment[380, 381] if the secondary restraint of an intact medial meniscus is retained.

5.6.1 Limitations

This in vitro study was designed to replicate clinical manual examination of A-P laxity, including the Lachman Test, which is an unloaded physical examination. The contributions of muscle loading, bodyweight and the shape of the polyethylene inserts will combine with the passive stability measured in this study to influence knee stability during weight bearing activity[375, 382], but was outside the scope of this study which focused on the effects of arthroplasty on the passive ligamentous contributions to A-P stability. The arthroplasty procedures were performed according to the anatomical landmarks available, with the assistance of the 3D printed-alignment device. However, the specimens did not include the ankle for referencing of the tibial cutting jig, for example, and no post-procedure radiographs were performed. Therefore, it was difficult to say with any certainty what the resulting alignment and posterior slope for each implant were. The relatively low loads in this study allowed the implants to be secured using minimal cementing, so that the PKA revisions would not damage the underlying bone and compromise the TKA. The lateral-sided procedures used a fixed-bearing device with a round-on-flat design. It is unknown what influence the use of a mobile bearing round-on-round device may have had on the results for the UKA-L, Bi-UKA or BCA-L tests. Therefore, the results of this study apply to a fixed-lateral design, but may not be generalisable when a lateral tibiofemoral mobile bearing device is *in situ*. This warrants further study. Some contemporary TKA implant systems report increased A-P stability due to a deep dish /

'ultra-congruent' polyethylene liner, as discussed in section 2.6.3[383]. The system used in this study does not have such a design, so the results may not be generalizable to all TKA systems and warrants further study.

5.6.2 Conclusions

This cadaveric study has reaffirmed the knowledge that UKA-M retains near-native A-P stability in the treatment of medial compartment OA. However, for the first time, it has also provided evidence of the near-native A-P stability of UKA-L and CPKA, whereas Posterior Cruciate Ligament-preserving TKA demonstrated increased laxity, particularly in anterior tibial translation.

5.7 Extensor Efficiency of the Knee

5.7.1 Publications

This section includes text and images from the following publications, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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Garner A, Dandridge O, Amis AA, Cobb JP, van Arkel RJ. The extensor efficiency of unicompartmental, bicompartmental, and total knee arthroplasty. Bone Joint Res. 2021 Jan;10(1):1-9. doi: 10.1302/2046-3758.101.BJR-2020-0248.R1.

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5.7.2 Motivation

The aim of this study was to quantify the efficiency of knee extension in vitro following UKA, BCA, and TKA to reveal how the different arthroplasties affect knee extensor function. Our null hypothesis was that there would be no differences in extension moment or efficiency between the different forms of arthroplasty compared to the native knee, or relative to each other.

5.7.3 Extension Rig

A knee extension rig was modified for this investigation (Appendix: Figure 13.1, Figure 13.2, Figure 13.3). The new iteration of the rig consisted of three sections. In the middle of the rig, sat a vertical mount for the femur. The specimens were potted with a bolt projecting from the pot proximally, in line with the long-axis of the femur. The bolt passed through the vertical support and was securely tightened with a nut, so as to avoid rotation of the femur during testing (Figure 5.26). The back of

the pot was marked so that the knee would be returned to the same orientation on the rig, with each repeated test.

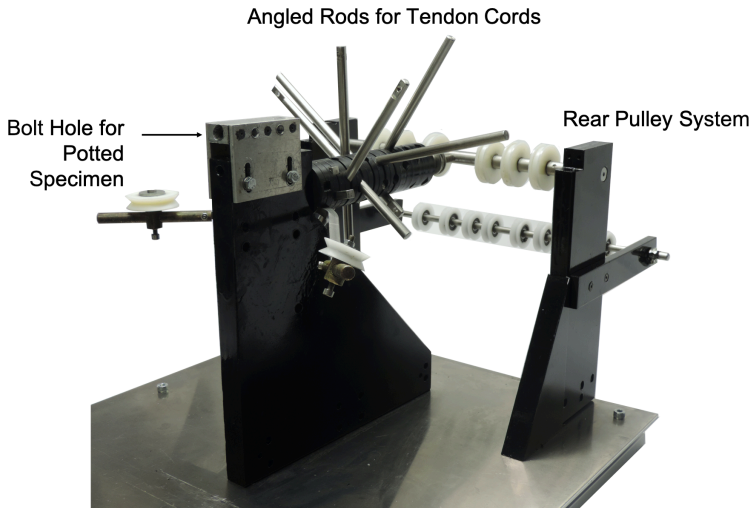


Figure 5.26. Extension Rig Middle and Rear sections showing femoral bolt hole and angled rods for tendon cords.

Toward the rear of the rig, different length rods were arranged to project at specific angles relative to the long axis of the femur (Figure 5.27, Figure 5.28). Each rod was fitted with a pulley at the end, over which the fabric-bound tendon cords were passed. The angles created by the rod represented the anatomical line of pull for the respective tendon [384, 385] simulating physiological knee extension[386]. The applied load totalled 225 N, which is sub-physiological, so as to prevent tearing of the cadaveric tendons, but distributed according to the reported cross-sectional area of each muscle[385] (Table 5.7).

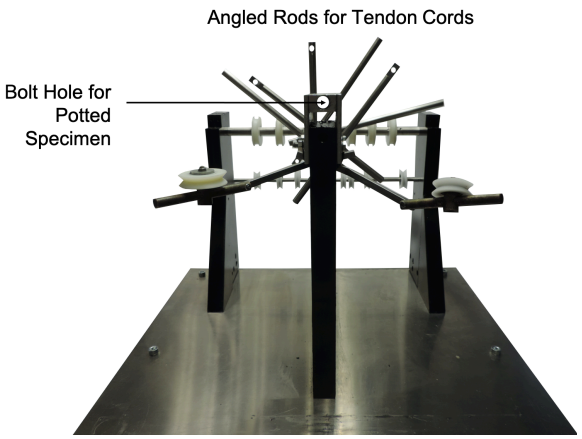


Figure 5.27. Axial view of Extension Rig Rear section, with the side supports removed, demonstrating angled rods for tendon cords and central bolt hole for femoral pot.

Tendon(s)	Load Direction Relative to Femoral Shaft Axis		Load (N)
	Anterior-posterior	Medial-Lateral	
Rectus Femoris & Vastus Intermedius	0° Anterior	0° Lateral	61.25
Vastus Lateralis Longus	0° Anterior	14° Lateral	57.75
Vastus Lateralis Obliquus	33° Posterior	35° Lateral	15.75
Vastus Medialis Longus	0° Anterior	15° Medial	24.5
Vastus Medialis Obliquus	44° Posterior	47° Medial	15.75
Iliotibial Band	6° Posterior	0° Lateral	30
Medial Hamstrings (Semimembranosus & Semitendinosus)	0° Posterior	0° Medial	10
Lateral Hamstrings (Long & Short head of Biceps Femoris)	0° Posterior	0° Lateral	10

Table 5.7. Loading weight and direction of pull relative to the femoral shaft axis for individually dissected quadriceps, iliotibial band and hamstring tendons.

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At the rear of the rig sit two rows of pulleys (Figure 5.28). Once through the rods, the cords from the quadriceps and iliotibial band pass over the top row of pulleys, then the second row, which is lower and projects more rearward, so that the hanging weights can move freely clear of the bench (Figure 5.29). As the knee flexes and extends, the tension in the tendon causes its respective hanging weight to rise and fall. Similarly, the hamstring tendon cords pass over the rear pulley system, but only the lower row as their direction of pull takes them beneath the upper row pulleys.

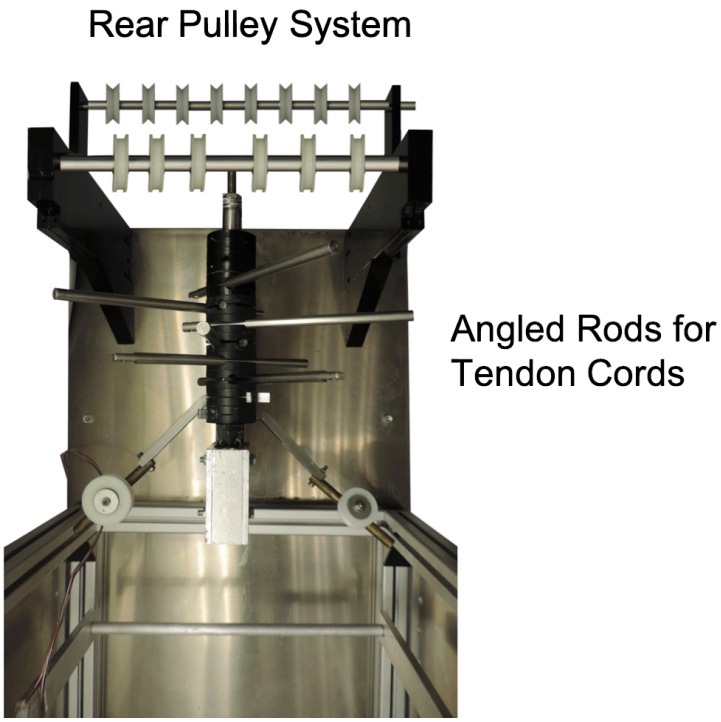


Figure 5.28. Aerial view of rear portion of extension rig demonstrating angled rods and two-tier pulley system

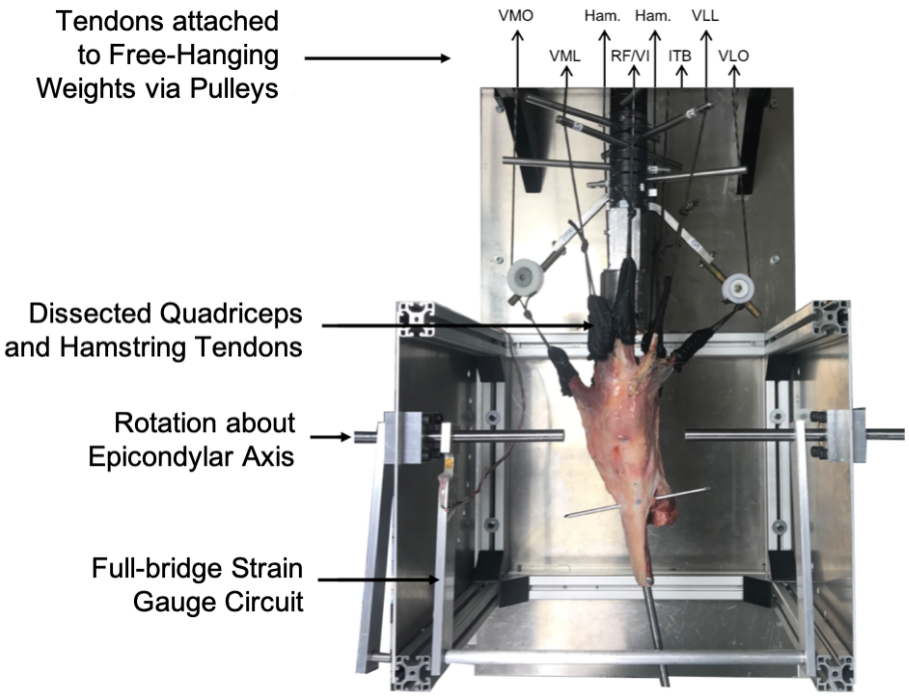


Figure 5.29. Aerial view of the extension rig, showing dissected tendons, from left to right. VMO, vastus medialis obliquus; VML, vastus medialis longus; Ham., semimembranosus and semitendinosus; RF/VI, rectus femoris with vastus intermedius; Ham., short and long head of biceps femoris; ITB, iliotibial band; VLL, vastus lateralis longus; VLO, vastus lateralis obliquus.

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Once mounted, the specimen projects into the front portion of the rig, whilst the weights hang freely over the bench at the rear (Figure 5.30)

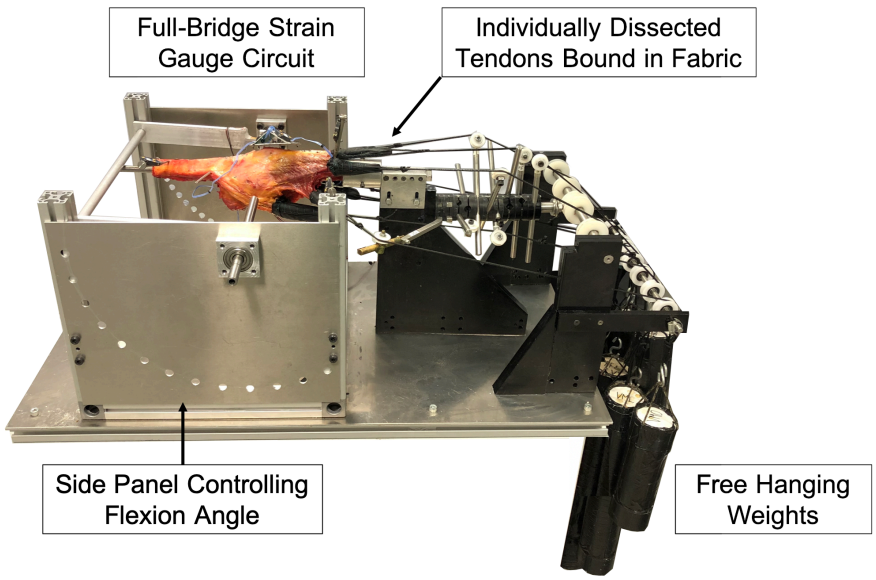


Figure 5.30. Extension Rig: Side view, mounted with cadaveric knee specimen in extension, with tendon loading to 225 Newtons.

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Panels sit either side of the specimen, adjustable in the proximal-distal and anterior-posterior planes, relative to the specimen, so that regardless of the size of the specimen, the transepicondylar axis is aligned to the extension axis of the rig (Figure 5.31, Figure 5.32) as previously described [386].

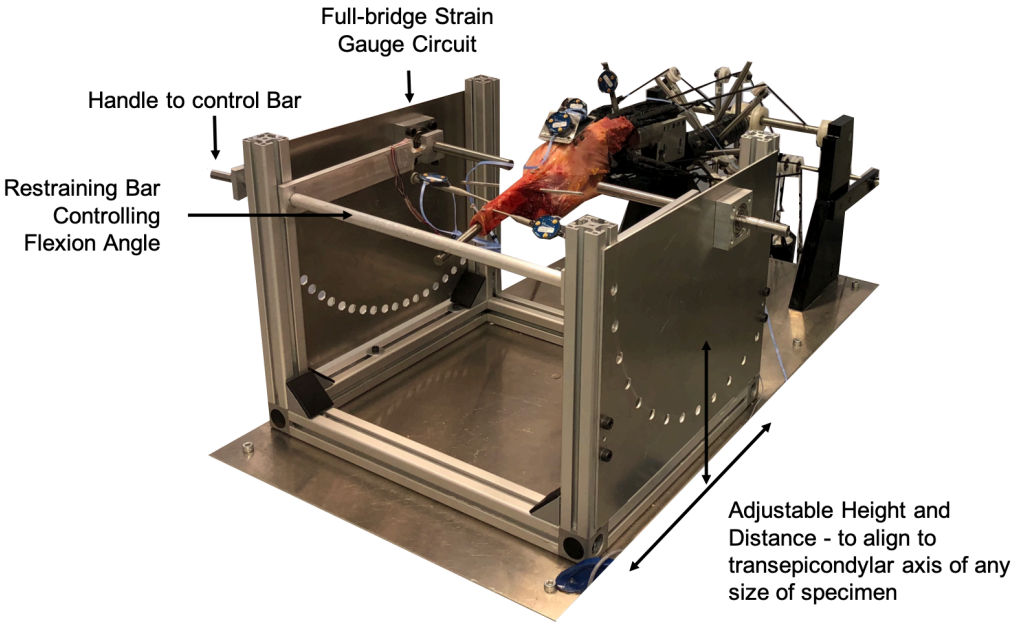


Figure 5.31. Oblique View Extension Rig Mounted with Cadaveric Knee in Full Extension, Demonstrating Adjustable sides and restraining bar to control the flexion-extension cycle.

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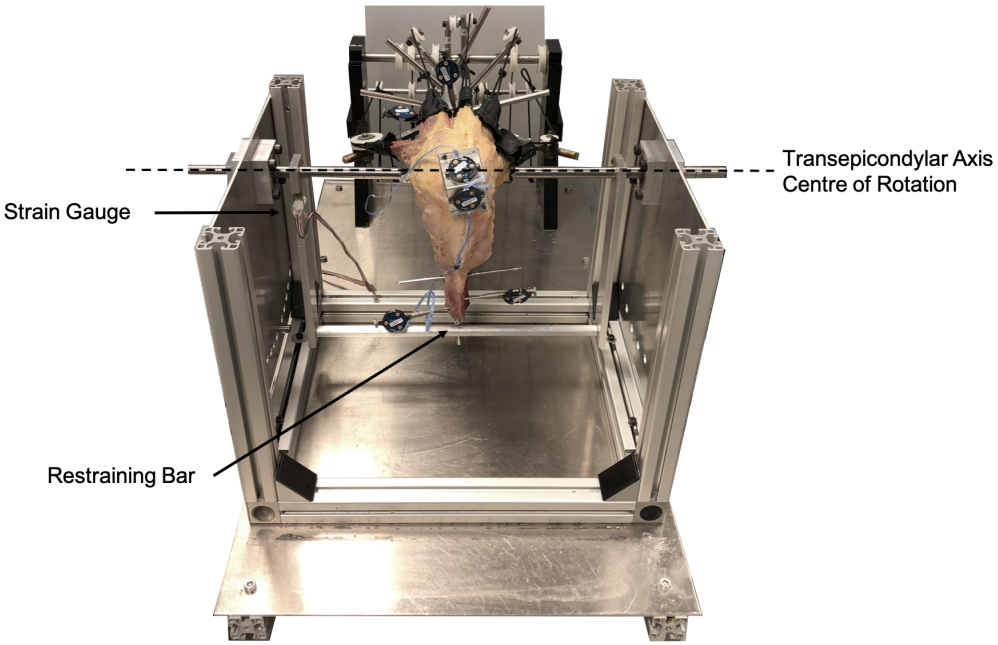


Figure 5.32. Front view of Extension Rig mounted with cadaveric knee at 90 degrees flexion, rotating about the Transepicondylar axis

The tibial intramedullary rod was restrained by a bar, connected to a calibrated full-bridge strain gauge circuit. A handle at the side of the rig is used to flex and extend the knee, acting as a 'stop' at each flexion angle (Figure 5.31). Restrained extension under muscle loading conditions enabled measurement of the extension moment, using a repeated measures design[348, 384-386, 388]. Measurements were taken from 110-0° knee extension, at 10° increments, repeated three times for each implant state (Figure 5.33).

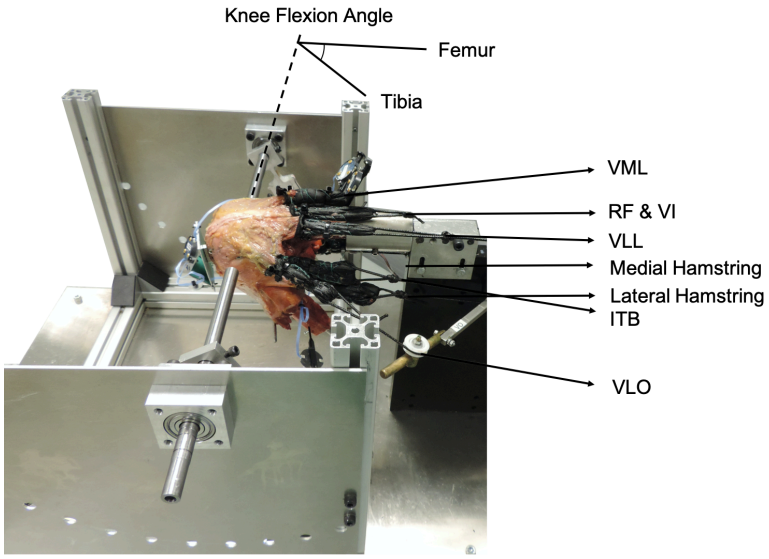


Figure 5.33. Knee Extension Rig, Lateral View, Mounted with a left cadaveric knee, shown in deep flexion, with a schematic representation of tendon loading. VMO cannot be seen from this view.

5.7.4 Validation of rig

The restraining bar was instrumented with a gauge that measured the strain in volts via a data logger. To convert this reading to force, the bar was loaded with weights of a known mass, the readings from which were plotted as volts against force (Appendix Figure 13.4). The readings were repeated five times and averaged in order to later convert the output readings into force measurements.

5.7.5 Data Analysis

Extensor efficiency was defined as the ratio of energy output by the extending knee through a range of flexion following arthroplasty, compared to the native knee. All specimens were subject to the same load (energy input), and therefore the output value is a 'relative' number, assuming the native

knee to be 100% efficient. The work output was calculated as the integral of the extension moment over a chosen flexion range. Five flexion ranges were examined. Four corresponded to daily activities that require the quadriceps activity to generate knee extension moments: the stance phase of gait at fast walking speeds (30-0°),[389] stair ascent (40-10°),[390] uphill walking (80-10°)[391] and sit-to-stand (100-0°).[392] The full experimental range was also examined.

The cadaveric intra-state repeats were averaged in MATLAB before statistical analysis in SPSS. Data were tested for normality with a Shapiro-Wilk Test and then analysed with repeated measures analysis of variance, RMANOVA, (α=0.05):

- A two-way RMANOVA of extension moment with independent variables implant state (native, Bi-UKA and TKA) and flexion angle (110°-0° in 10° increments).
- One-way RMANOVAs of work done with independent variable implant state, for the full range of flexion angles (110°-0°), and for the subset of flexion angles associated with fast gait[389] (30°-0°).
- Post hoc paired t-tests with Bonferroni correction were applied when differences across tests were found. Adjusted p-values, multiplied by the appropriate Bonferroni correction value in SPSS, were reported.

5.8 Results

5.8.1 The Native Knee

Between 10° and 20° of flexion, the mean extension moment of the native knee was at its highest, at 4.7 Nm (SD 1.2) (Figure 5.34, Figure 5.35). There was a large reduction in mean extension moment to 3 Nm (SD 1.7) in terminal extension (paired t-tests $p < 0.015$), and to a minimum of 2.5 Nm (SD 0.5) between 70° and 80° flexion (paired t-tests $p < 0.001$).

5.8.2 Medial Compartment Procedures

The addition of a UKA-M or a BCA-M caused no reduction in mean peak extension moment at 20° flexion (UKA-M 4.7 Nm (SD 0.6), BCA-M 4.6 Nm (SD 0.6)) while the insertion of a TKA resulted in a mean extension moment of 2.8 Nm (0.6), only 60% of the normal value (paired t-test $p < 0.001$; (Figure 5.34). The size of the difference depended on the angle of knee flexion (RMANOVA $p < 0.001$;

Figure 5.34). Large reductions in knee extension moment were measured following TKA at low angles of flexion (10° to 30°) compared to the native knee and the PKA procedures (mean decreases of 1 Nm (SD 0.6) to 2.3 Nm (SD 0.9), or 28% to 61%; paired t- tests $p < 0.01$). In mid-flexion (40° to 60°), no difference was detected between any implant state, except for at 40° flexion, where the mean extension moment was 0.8 Nm (SD 0.6) higher for BCA-M than TKA (paired t-test $p = 0.04$). From 70° to 90°, BCA-M generated lower extension moment compared to TKA (mean differences < 1.0 Nm (SD 0.7); paired t-tests $p < 0.04$) and the native knee (mean difference < 0.9 Nm (SD 0.6); paired t-tests $p = 0.05$ at 70° and 90°; paired t-test $p < 0.01$ at 80°). A very small increase in moment was also measured following TKA compared to the native knee at 90° (mean 0.2 Nm (SD 0.1); paired t-test $p = 0.02$). All states were similar at flexion angles of 100° or higher.

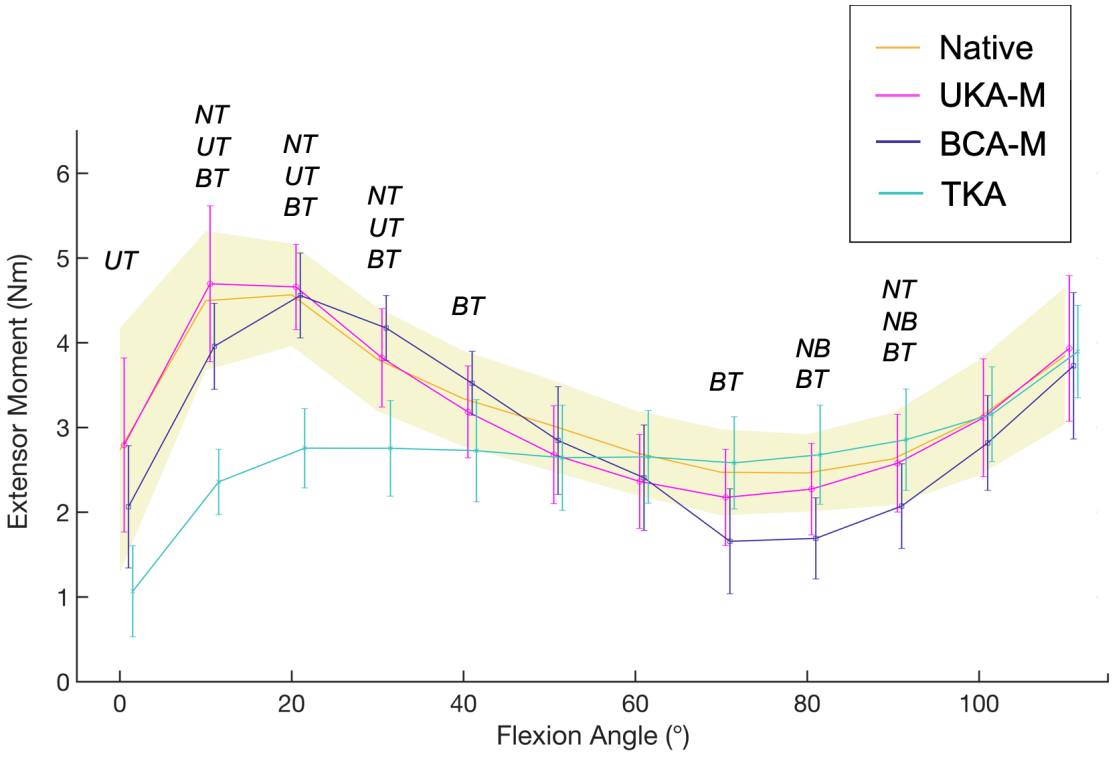


Figure 5.34. Static flexion angles against mean extension moment (Nm) for native knees, medial unicompartmental knee arthroplasty (UKA-M), medial bicompartmental arthroplasty (BCA-M) and total knee arthroplasty (TKA); 95% confidence intervals with a shaded yellow area for the native knee, and bars for the implanted knees. Italicised letters indicate pairwise statistical differences ($p<0.05$): NU, native versus UKA-M; NB, native versus BCA-M; NT, native versus TKA; UB, UKA-M versus BCA-M; UT, UKA-M versus TKA; BT, BCA-M versus TKA.

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5.8.3 Lateral Compartment Procedures

For the lateral group, a similar pattern was seen (Figure 5.35). The normal knee delivered its maximal mean extension moment of 4.9 Nm (SD 1.4) at 10°, while the lateral UKA's maximum mean extension moment of 4.5 Nm (SD 1.2) was at 20°, as was the BCA-L, which delivered a mean 4.6 Nm (SD 1.1). Conversely, the low-flexion peak for TKA was observed at 30° and was 29% lower than normal at a mean 3.5 Nm (SD 0.6). TKA generated reduced extension moment compared to: the native knee in full extension; all other states at 10°; native and BCA-L at 20°; and BCA-L at 30° (mean decreases of 0.9 Nm (SD 0.5) to 2.6 Nm (SD 1.8), or 22% to 83%; paired t-tests $p < 0.03$). All states were similar from 40° to 60°. At 70°, BCA-L produced a smaller extension moment compared to native and TKA states (mean decrease < 0.9 Nm (SD 0.3); paired t-tests $p < 0.01$), and TKA had a higher mean extension moment than UKA-L (0.4 Nm (SD 0.3); paired t-test $p = 0.04$). At 90°, BCA-L produced a lower moment than UKA-L (mean difference 0.7 Nm (SD 0.4); paired t-test $p = 0.02$). At 110°, the extension moment after UKA-L was higher than native and TKA, while BCA-L was higher than TKA (mean increases < 0.8 Nm (SD 0.4); paired t-tests $p < 0.01$).

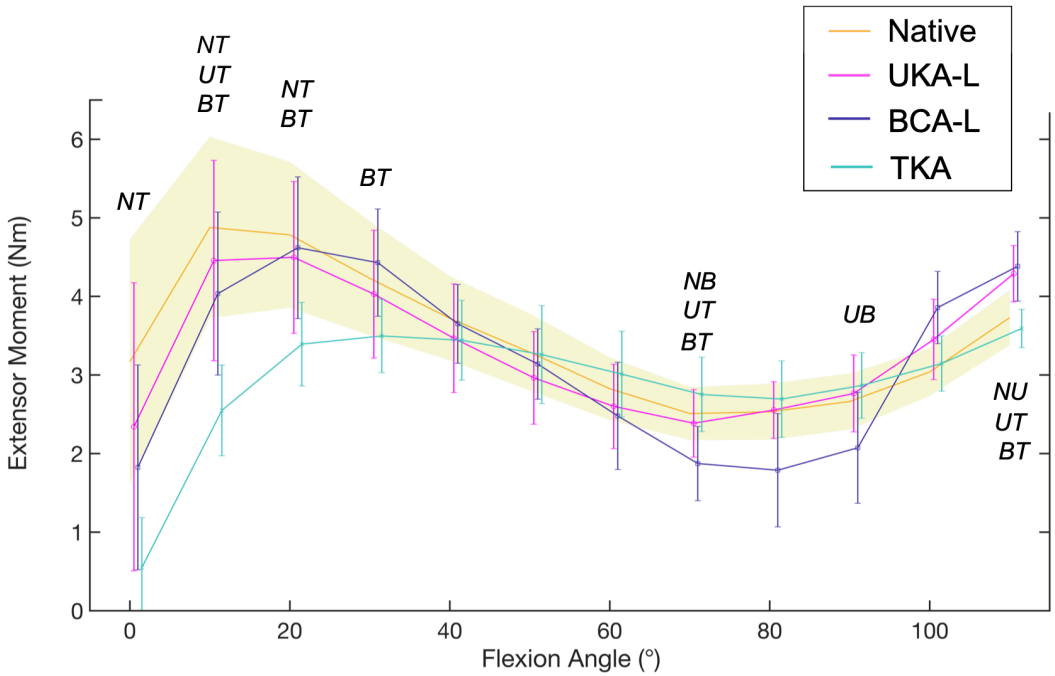


Figure 5.35 Static flexion angles against mean extension moment (Nm) for native knees, lateral unicompartmental knee arthroplasty (UKA-L), lateral bicompartmental arthroplasty (BCA-L) and total knee arthroplasty (TKA); 95% confidence intervals with a shaded yellow area for the native knee, and bars for the implanted knees. Italicised letters indicate pairwise statistical differences ($p<0.05$): NU, native versus UKA-L; NB, native versus BCA-L; NT, native versus TKA; UB, UKA-L versus BCA-L; UT, UKA-L versus TKA; BT, BCA-L versus TKA.

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5.8.4 The Bi-Unicondylar Set

Mean extension moment for the native knees peaked at 20°, at 5.0Nm (SD 0.3) (Figure 5.36) notably decreasing toward terminal extension: 1.5Nm (SD 0.6) and toward a minimum of 2.4Nm (SD 0.1) at 70° flexion before increasing once again in deep flexion 3.6Nm (SD 0.4) at 110°. The effects of implant state on extensor moment depended on knee flexion angle ($p<0.001$, Figure 5.36).

The addition of Bi-UKA made little difference at terminal extension 1.7Nm (SD 0.6, $p=1$) or 20° 4.8Nm (SD 0.6, $p=0.4$). Between 40° and 100° Bi-UKA extensor moments were lower than native (all $p<0.05$), with minimum moment of 1.65Nm (SD 0.2) at 70° (Bi-UKA vs native 31% reduction, $p=0.02$). Bi-UKA extensor moments were within the normal range at 100° (Native 2.9Nm SD 0.3, Bi-UKA 2.7Nm SD 0.3. $p=1$) and 110° flexion (Bi-UKA 4.3Nm SD 0.4, 19% increase vs native $p=0.08$).

TKA had a highly significant impact on extensor moment at 10° (2.3Nm SD 0.2, vs native $p<0.001$, vs Bi-UKA $p=0.002$), 20° (3.0Nm SD 0.2 40% reduction vs native $p<0.001$, 38% reduction vs Bi-UKA, $p<0.001$) and 30° (3.1Nm, SD 0.1, vs native $p<0.001$, vs Bi-UKA $p<0.001$). At 40° both Bi-UKA and TKA were reduced compared to the normal range (TKA 3.2Nm SD 0.2, vs native $p<0.001$, vs Bi-UKA $p=0.06$). From 50°-110°, TKA extensor moments were within the native range (all $p>0.05$) recording a minimum moment of 2.34Nm (SD 0.2) at 70° and a near native moment at 110° (3.6 SD 0.2, $p=1$).

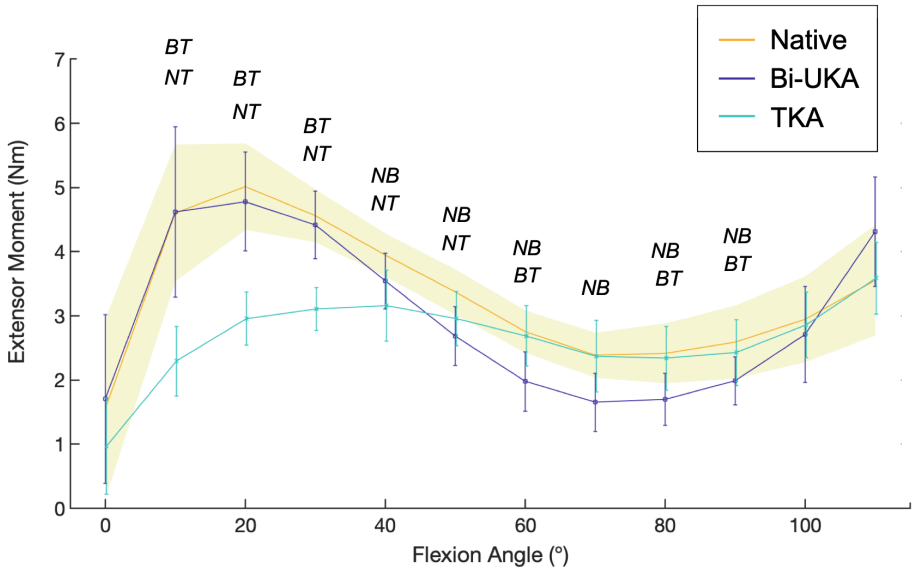


Figure 5.36. Static flexion angles against mean extension moment (Nm) for native knees, Bi-Unicondylar Knee Arthroplasty (Bi-UKA) and total knee arthroplasty (TKA). 95% confidence intervals with a shaded yellow area for the native knee, and bars for the implanted knees. Italicised letters indicate pairwise statistical differences ($p<0.05$): NB, native versus Bi-UKA; NT, native versus TKA; BT, Bi-UKA versus TKA.

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5.8.5 Extensor Efficiency

Compared to the native knee, arthroplasty affected the work output of the extensor mechanism (Figure 5.37, Figure 5.38, Figure 5.39). Across the full range of motion (0° to 110°), TKA demonstrated a mean > 14% (SD 9%) reduction in extensor efficiency (paired t-tests $p < 0.02$). Conversely, differences between UKA-M and BCA-M (Figure 5.37), and UKA-L and BCA-L (Figure 5.38), respectfully, were not found. Over the full flexion range (Figure 5.39), TKA were less efficient than Bi-UKA ($p<0.03$) and native knees (21% reduction, $p<0.001$).

For the quadriceps active range of uphill walking (80° to 10°), stair ascent (40° to 10°), and gait (30 to 0°), no differences were detected between medial and lateral UKA and their BCA equivalents, and native knee work output (Figure 5.37, Figure 5.38). Bi-UKA demonstrated near-normal efficiency in the gait range (30°-0°, 2% reduction, $p=1$), whilst TKA were less efficient than native (42% reduction, $p=0.001$) and Bi-UKA ($p=0.001$, Figure 5.39).

For the sit-to-stand range (100° to 0°), UKA-M, UKA-L, and BCA-M were similar to native (Figure 5.37, Figure 5.38), but BCA-L was a mean 10% (SD 8%) less efficient (paired t-test $p = 0.04$, Figure 5.38). Efficiency after TKA was greatly reduced for all examined daily activity ranges compared to the native state (paired t-tests $p \leq 0.02$), with the least reduction seen for uphill walking (mean 12% (SD 7%) reduction; paired t-test $p = 0.01$) and the greatest seen for the stance phase of gait (mean 43% (SD 13%) reduction; paired t-test $p < 0.001$).

Compared to the medial compartment procedures, TKA was less efficient than UKA-M and BCA-M in stair ascent and gait (mean decreases 35% (SD 10%) to 45% (SD 11%); all paired t-tests $p < 0.001$, Figure 5.37), and UKA-M for sit-to-stand (mean reduction 17% (SD 10%); paired t-test $p = 0.01$). Comparing to the lateral compartment procedures, TKA was less efficient than BCA-L for the stair ascent (mean 23% (SD 10%) reduction; paired t-test $p < 0.01$) and gait ranges (mean 32% (SD 19%) reduction; paired t-test $p = 0.01$, Figure 5.38).

In the Bi-UKA set, Bi-UKA was near native (4% reduction, $p=0.4$) whilst TKA lost 37% efficiency ($p<0.001$) in the stair ascent range (40°-10°). Both arthroplasty states were less efficient than native for the slope ascent (80°-10°) and sit-to-stand (100°-0°) ranges ($p<0.05$), however, TKA were least efficient ($p<0.05$ vs Bi-UKA, Figure 5.39).

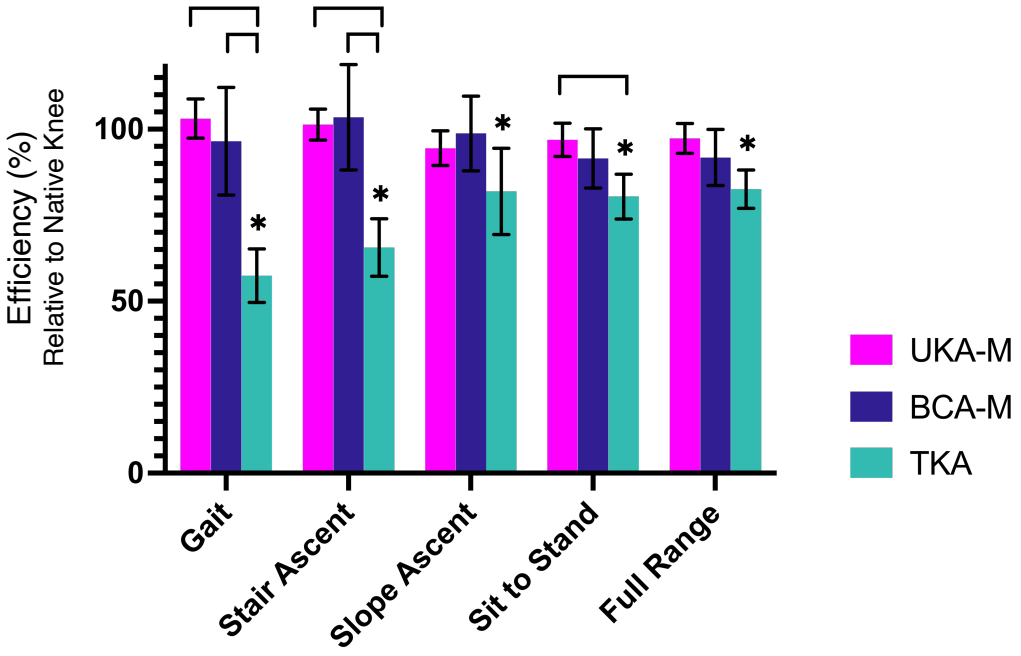


Figure 5.37. Work output by the extending knee during different activities relative to the native knee (assumed to be 100% efficient) for Group 1: Medial Unicompartmental Arthroplasty (UKA-M), Medial Bicompartmental Arthroplasty (BCA-M) and Total Knee Arthroplasty (TKA). The asterisks (*) indicate data statistically different from the native knee, brackets indicate differences between the arthroplasties (paired t-tests $p < 0.05$).

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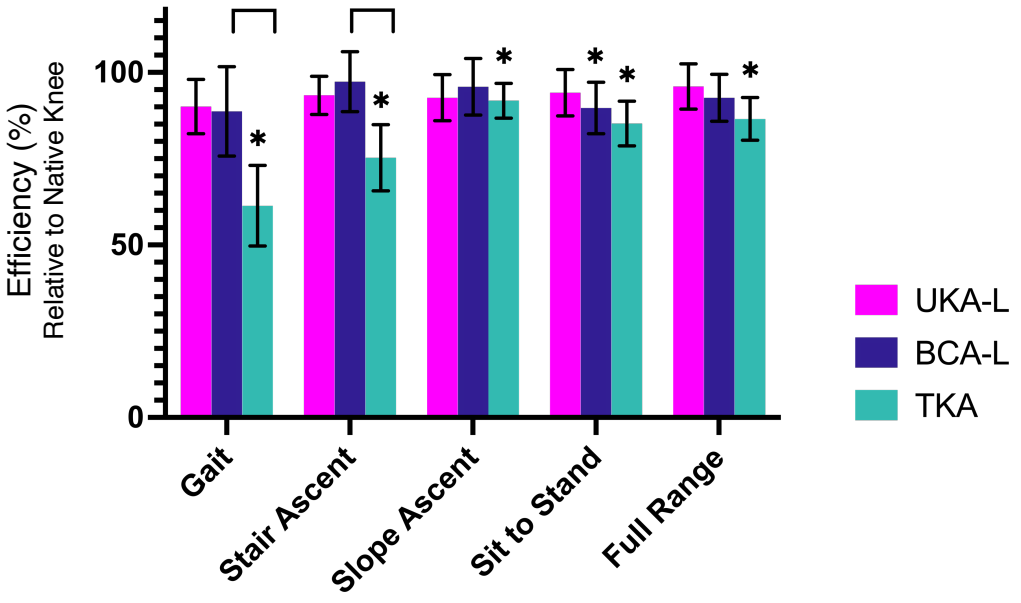


Figure 5.38. Work output by the extending knee during different activities relative to the native knee (assumed to be 100% efficient) for Group 2: Lateral Unicompartmental Arthroplasty (UKA-L), Lateral Bicompartmental Arthroplasty (BCA-L) and Total Knee Arthroplasty (TKA). The asterisks (*) indicate data statistically different from the native knee, brackets indicate differences between the arthroplasties (paired t-tests $p < 0.05$).

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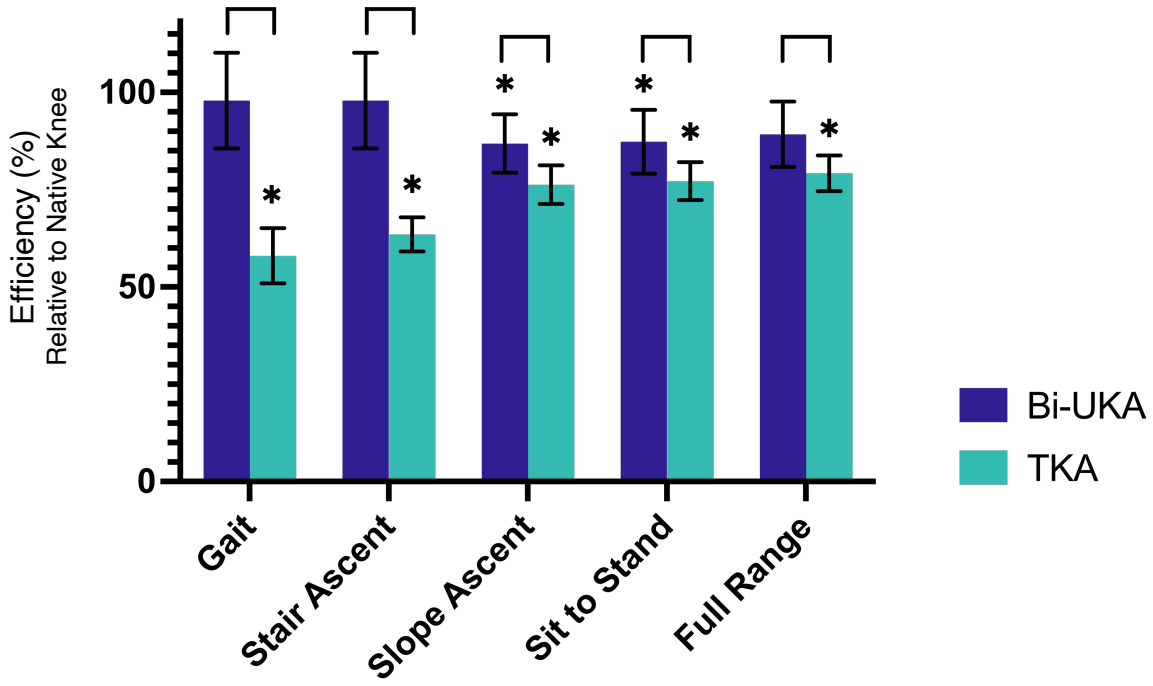


Figure 5.39. Work output by the extending knee during different activities for each implant state relative to the native knee (assumed to be 100% efficient). Arthroplasty sequences for Group 3: Bi-Unicondylar Arthroplasty and Total Knee Arthroplasty (TKA).

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Efficiency data in Figure 5.37, Figure 5.38, Figure 5.39 are displayed as mean with 95% confidence interval work output by the extending knee over different ranges of motion for the different arthroplasty procedures as a percentage of the native knee work output. Data for gait (30 to 0°), stair ascent (40° to 10°), uphill slope walking (80° to 10°), sit-to-stand (100° to 0°), and full (110° to 0°) ranges of knee flexion are shown.

5.9 Discussion

The most important finding of this study is that UKA, BCA and Bi-UKA make little impact on the efficiency of the extensor mechanism, while the negative impact of TKA on extensor function is substantial, with a reduction in extension moment of over 40% towards terminal knee extension. Following UKA, no differences were detected in either extension moment or efficiency. The addition of a PFA resulted in a small drop in extension moment between 70-90° flexion but when examined in the context of the full range associated with the quadriceps active range of activities of daily living, extensor efficiency was largely unaffected. Similarly, following Bi-UKA, there was a small drop in efficiency the flexion ranges associated with slope walking and sit-to-stand activities, however,

across the full flexion range, differences did not reach statistical significance. Conversely, in all three test sets, following TKA, large decreases in extension moment at low flexion angles resulted in 12-43% drops in extensor efficiency, in particular over angles associated with common activities of daily living. This suggests that in order to achieve the same function during these activities, TKA patients expend significantly more energy. Most notably, this was observed during activities associated with increased levels of quadriceps activity and high cycle numbers, such as fast walking.[389, 393, 394]. These findings corroborate those of others, who have shown abnormal flexion-extension moments following TKA, attributing this to reduced quadriceps effectiveness[391, 395].

The vast majority of patients benefit from TKA, experiencing relief of pain and low revision rates compared to partial knee arthroplasty (PKA)[396]. Patients with increased extensor strength report better outcomes,[397] however, TKA is known to reduce extensor strength relative to native knees,[398, 399] impacting gait and other functional activities. PKA has been associated with restoration of kinematics and gait toward that of the native knee[400], improved range of movement and faster return to desired physical function[401]. The improved function of PKA is, in part, a consequence of retention of the anterior cruciate ligament (ACL), which is otherwise sacrificed for nearly all TKA designs. Posterior-stabilized TKA designs also require resection of the posterior cruciate ligament (PCL). In one study of consecutive patients' functional cruciate ligaments were resected in 95% of cases,[402] regardless of the functional integrity of either ligament. Loss of the cruciate ligaments is classically associated with knee instability, has been recently shown to affect intraoperative gap balancing,[403] and now the data from the current study suggest it may also affect knee extensor efficiency. The mechanism for this may be the increased anterior translation and the associated reduction in patellar tendon angle resulting from the loss of ACL function[404, 405]. This study further suggests that conversion of a PKA to a BCA in the event of subsequent degeneration may preserve extensor efficiency and potentially improve functional outcomes for the patient.

An in vivo kinematic study found abnormal sagittal kinematics following TKA, but not UKA-M, for the terminal 20° of open-chain knee extension.[405] Similarly, previous *in vitro* studies have demonstrated that single UKA-M implants retain near-native kinematics of the knee,[406] which are significantly altered following TKA.[407] Isolated PFA replacement has been reported to replicate native extension moments, meanwhile significant reductions from 0-50° flexion are seen with cruciate-retaining and posterior-stabilized TKA designs.[386] Our study supports the findings of these studies, but furthers those findings to address isolated arthrosis of the lateral compartment, and bicompartmental arthrosis.

5.10 Limitations of the overall cadaveric study

By undertaking a repeated measures design, with the only variable being implant state, this cadaveric model eliminated confounding factors, including muscle strength and variation in anatomy. However, since testing was under static conditions with constant loading, the model is unable to replicate true in vivo kinematics or physiological muscle loading conditions, or the soft-tissue response of the healed post-operative knee. Binding tendons to muscle loads dictated a maximum load that could be applied before tearing occurred. The applied loads were an order of magnitude lower than normal physiological conditions. Here, we prioritized loading in a physiological direction and with the tensions shared among muscles according to their PCSAs, over magnitude of force applied, with the consequence being that our efficiency data required normalisation. The specimens varied in size, yet the load remained constant. From the data collected, it was difficult to quantify the impact of this. The mean BMI for the donors was 24 Kg/m^2 (SD 3 Kg/m^2) and normally distributed. Therefore, in all probability, any differences would be very small, and likely to cancel each other out, especially given that the applied loads were significantly lower than the normal physiological loads. The distribution of load is based on a significant number of previous studies, and is calculated as a proportion of cross-sectional area of each tendon. Therefore, the size of the donor and/or specimen does not necessarily correspond to muscle mass or tendon size. In view of these complexities, the decision was taken to simplify the model and use the same loads for all specimens.

The cadavers were age-appropriate but without obvious evidence of osteoarthritis or joint disease. It is likely that the ACLs were healthier in these specimens than in joints with end-stage osteoarthritis, which may have a bearing on the results. The native alignment profile for each specimen was unknown, so differences in joint line obliquity or tibia vara, for example, were unaccounted for.

Repeated access to the knee was required, necessitating re-opening and closure of the transpatellar approach. Consistent technique whilst tensioning the sutures and tightening the screws was intended to minimise possible variation, some disparity may have occurred. Previous work suggested that the impact of this was minimal[349] and hence it was unlikely to change the outcome of this work.

TKA had to be the final implant state due to its invasiveness. Prior PKA may have influenced the TKA bone cuts. We minimised any potential impact of this by minimising the amount of cement used to

fix the PKA components. Evidence of minimal impact of prior PKA included: 1) visual inspection of the bones cuts prior to TKA implantation (Figure 5.14, Figure 5.16), 2) in all but one knee, 10-12 mm polyethylene bearings were sufficient to balance the knee which is representative of clinical practice (if bone stock were lost, a thicker bearing would be required), 3) pilot testing of knees without prior TKA all fell within the 95% confidence interval of the data presented in this study, indicating no large effects of the prior PKA on the kinematics measured in this study[355]. Our surgical technique referenced the TKA from the implanted UKA; some authors consider UKA to TKA to be effectively a primary TKA with no differences in patient outcomes, whilst others report that prior UKA can negatively influence TKA outcomes[408-412]. Clinically, data suggest that walking on a slope with a TKA in situ is functionally more difficult than post-UKA.[413] However, in this study, no differences were detected over this range of flexion. Differences in slope walking may be a consequence of other factors, such as loss of proprioception following resection of the cruciate ligaments, rather than differences in extensor function.

A cadaveric model was chosen, as it enabled the implant stages to be performed sequentially. To date, little information is available regarding the biomechanics of CPKA, meaning that such an experiment *in silico,* for example, would prove very difficult, as only limited data are available upon which to build an accurate computational model. Further, *in silico* data may reflect the "perfect" operation, however, one criticism of CPKA is that the procedures are technically demanding for surgeons, and that early data from CPKA suggested that, in part, some of the adverse outcomes were as a consequence of challenging surgery[8, 275]. Complications include fracture and tibial eminence avulsion, which did not occur during this study, but are described.

Using a cadaveric model provided the opportunity to recreate a more realistic scenario, suggesting the data may be more representative of the *in vivo* biomechanics, with a degree of variation from one procedure to the next. Sufficient numbers of specimens were included in the study to account for this. The *in vitro* procedures were performed by me, a trained but not expert PKA / CPKA surgeon. It is acknowledged that the learning curve was steep, which is both a limitation of the study and of widespread adoption of CPKA in clinical practice. No post-surgical radiographs were performed, which would have been useful to determine component alignment, for example. The laboratory has since invested in Mini-C-Arm fluoroscopy, which will help overcome this issue in the future.

5.11 Conclusion

This study found that partial knee arthroplasty preserves near-normal extensor function, whilst TKA had substantially inferior extensor function compared to UKA and BCA. This may help explain the functional and satisfaction differences observed between partial and total knee arthroplasty. BCA offers an alternative to TKA with some biomechanical advantages for those whose arthrosis extends into a second compartment, and warrants further clinical investigation.

5.12 Chapter Summary

Chapter 5 has explored the cadaveric biomechanical properties of partial and combined partial knee arthroplasty. Several new insights have been gained: preservation of near-native Anterior-Posterior stability has been demonstrated and described in relation to UKA-M previously, however, to date, there has been little evidence of this in relation to UKA-L, or the CPKA procedures. The marked differences between the partial procedures and TKA are significant, in that they suggest for the first time that ACL-preserving Anterior-Posterior stability can be retained, to within the limits of the native knee, in the treatment of isolated lateral and two compartment OA. Mid-flexion instability is one of the most significant limitations of TKA and this data may suggest an alternative treatment modality, worth of investigation in vivo. Second, the preservation of extensor efficiency with medial and lateral UKA and BCA in comparison to TKA contributes toward out understanding of measurable in vivo weakness and patient reported dissatisfaction when undertaking quadriceps-active activities including fast-walking, sit-to-stand, hill and stair ascent. The increased anterior laxity with Bi-UKA indicates the important contribution the menisci make to joint stability. However, the anterior-posterior stability of Bi-UKA is still significantly greater than that of TKA, which suggests there may be a measurable improvement in vivo, yet to be explored.

6 The Gait of Compartmental Arthroplasty

Publications

This chapter includes text and images from the following publications, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. Medial bicompartmental arthroplasty patients display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients. Knee Surg Sports Traumatol Arthrosc. 2021 Oct 23. doi: 10.1007/s00167-021-06773-8

Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. The compartmental approach to revision of partial knee arthroplasty results in nearer-normal gait and improved patient reported outcomes compared to total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2021 Aug 20. doi: 10.1007/s00167-021-06691-9.

Contributions

The majority of the work in this chapter was independent, however, the following people made certain, significant contributions:

- Testing on the instrumented treadmill were conducted by myself, Miss Rhiannon Lambkin (gait laboratory assistant) and Dr Amy Maslivec (gait laboratory assistant). Some of the earlier control subjects had been tested by Mr Anatole Wiik (clinical research fellow), Miss Victoria Manning (gait laboratory assistant) and Miss Brogan Guest (Physician Associate).

- The MATLAB script used to process the data from the treadmill were originally written by Dr M Brevadt, research assistant, MSk Lab. For the purposes of this study, it was modified by Oliver Dandridge and Amy Garner with advice from Dr Simon Harris (Senior Researcher)

- All other work conducted by Amy Garner

6.1 Introduction

Gait analysis, the study of motion, is a quantifiable way of measuring body movement and mechanics. Early examples date back to Aristotle, through his writings *De Motu Animalium* (On the Gait of Animals). Measurement of human biomechanics, movement and gait were first formally reported in the 1890s[414]. By the turn of the 20th century, the rapidly evolving technology of photography and cinematography made it possible to capture motion sequences that would otherwise be too rapid to observe with the naked eye. In the 1970s, gait analysis was proving crucial in understanding pathological movement disorders, including Cerebral Palsy and Parkinson's Disease, made possible by advancements in video technology that enabled frame-by-frame analysis of motion pictures. The short leap to assessment of Orthopaedic disorders was well-established by the 1980s. Ever since, gait analysis has been shown to be a repeatable and reliable method of understanding the biomechanics of musculoskeletal disease, and comparing the outcome of alternative treatments or procedures.

6.2 First Principles

The gait cycle of the adult human biped is measured from heel-strike to heel-strike. The first 60% of the cycle is referred to as the stance phase, during which the leg accepts weight and can provide single limb support whilst the foot is in contact with the walking surface. The final 40% of the cycle is the swing phase. Here, the foot passes freely beneath the body, in a forward direction. As alternate limbs cycle, the body advances (Figure 6.1).

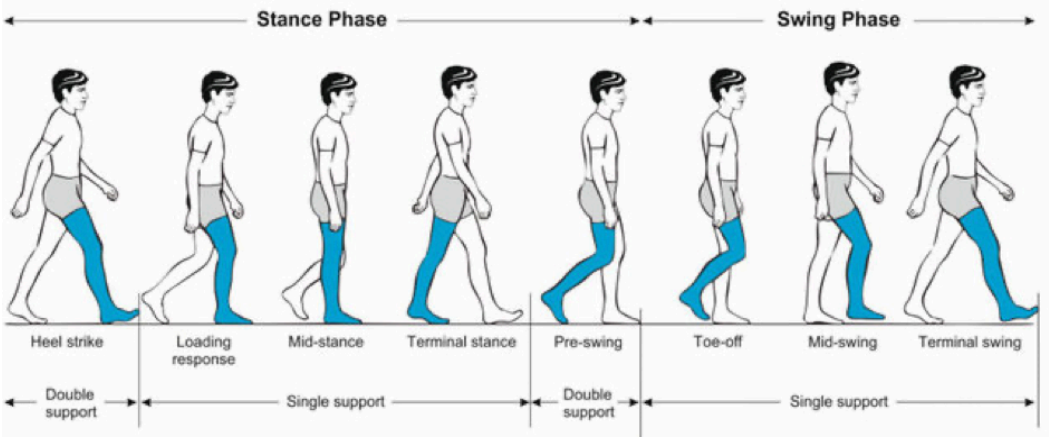


Figure 6.1 Phases of the normal gait cycle. CC BY 4.0 [415]

The stance phase begins when the foot makes initial contact with the ground, referred to as 'heel strike'. The hip is stabilised by the coordinated contraction of the gluteal and hamstring muscles and adductor magnus. The quadriceps eccentrically contract, as does tibialis anterior, enabling the limb to accept body weight. The knee flexes, lowering the centre of gravity and absorbing the shock of heel strike. This initial 'double limb' loading response transfers weight to the supporting limb and continues until the opposite limb is elevated. Plantar flexion is controlled by eccentric contraction of the ankle dorsiflexors, and the knee is stabilised by contraction of the quadriceps, counteracting the flexion moment about the knee.

During 'mid-stance' body weight is supported by the single limb, stabilised by eccentric contraction of gluteus medius, gastrocnemius, soleus and plantaris. Mid-stance is said to start as the opposite limb is elevated, and continues until the ankles align in the coronal plane.

Terminal stance begins as the supporting heel rises, ending as the opposite heel makes contact with the walking surface. The body remains supported by the single limb. Tibialis posterior and the toe flexors contract in anticipation of pre-swing, which begins as the opposite limb makes contact, returning the body to double limb support. The hip flexors contract and the advancing limb is propelled forward.

Swing phase begins at 'toe off': the knee flexes as the limb elevates, whilst the body is supported by the opposite limb. The leg is advanced by the concentric contraction of the hip flexors. Maximal knee flexion marks the start of mid-swing, with ankle dorsiflexion facilitating clearance of the foot from the ground. As the tibia becomes vertical, terminal swing begins. The action of the hamstring muscles results in deceleration of the limb, in anticipation of heel-strike.

A number of temporospatial measures are important when analysing gait (Figure 6.2)

Speed:

- Walking speed: the horizontal distance travelled in meters (m) during one second (s) of walking.
- Top Walking Speed (TWS): the fastest comfortable walking speed or the highest walking speed before running. For the purposes of this thesis, it will be described in kilometres per hour (km/h).
- Hof Speed (H): scaling of speed to a dimensionless number, to account for differences in leg length between subjects[416], also known as the Froude number, defined as:

$$\hat{v} = \frac{v}{\sqrt{g l_0}}$$

Where: $\hat{v}$ = Hof speed

v = Velocity (m/s)

g = acceleration of gravity (=9.81 m/s^2 on earth)

l_0 = Leg Length from greater trochanter to floor

Distance (Figure 6.2):

- Step length: the horizontal distance travelled between initial contact of alternating feet.
- Step width: the distance between the feet at initial contact, during consecutive steps, measured perpendicular to the horizontal plane.
- Stride length: the horizontal distance from initial contact to initial contact of the same foot.

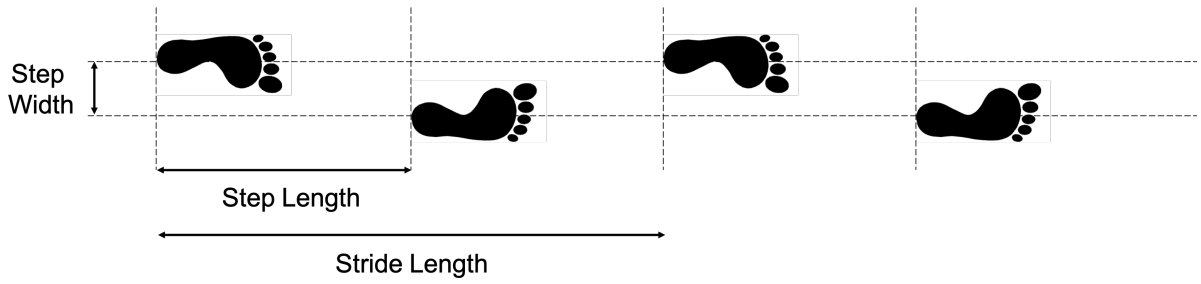


Figure 6.2. Cartoon depiction of the gait cycle indicating step width, step length and stride length

Time:

- Cadence: the number of foot strikes per minute
- Contact time: the period in seconds from initial contact to ipsilateral toe-off
- Step time: the period in seconds for one step
- Gait cycle (stride) time: the period in seconds for one stride
- Single support time: the period in seconds when only one foot is in contact with the ground

Double support time:

- the period in seconds during which both feet are in contact with the ground.

6.3 The instrumented treadmill as an alternative to overground walking

Traditional overground gait laboratories consist of a walkway, with load transducers, known as force plates, embedded in the floor. As the subject walks, they make contact with the force plates enabling the resulting Ground Reaction Forces, moments and temporospatial parameters to be measured. Often, force data may be combined with motion capture, recorded by a series of cameras located around the walkway. Mobile segments are labelled with reflective markers, enabling motion sequences to be computed based on the three-dimensional trajectory of each marker. The gait analysis of this thesis focuses on force plate data; therefore, motion capture will not be further discussed, except to say that it is a useful and sophisticated tool to investigate and understand the kinematics of joint replacement.

The instrumented treadmill is an alternative to over ground gait measurement. Data is captured with every step, by force plates beneath the moving belt, reducing the need for precise foot placement and increasing reliability[417]. This is advantageous compared to overground analysis, where a relatively small number of steps are recorded with each pass along the walkway, greatly increasing the number of trials required to capture equivalent data.

The speed and gradient of the treadmill may be increased and decreased as required, whereas overground speeds are typically self-selected, inconsistent and differ between subjects, making direct comparisons more difficult. Testing at top walking speeds enables individuals to be measured at the upper limits of their function, where more subtle differences in performance can be detected with greater accuracy. Earlier work from our laboratory has demonstrated significant differences in

top walking speeds between UKA and TKA[418, 419] which are often not detected at slower walking speeds[420].

A number of studies indicate that fundamental kinetic and kinematic parameters are similar between overground and treadmill walking[421-423]. Differences continue to be debated[424], specifically, treadmill walking can be associated with a shorter step length[425], higher cadence and reduced overall stance phase[426, 427]. Further, whilst the predictable nature of treadmill gait is a useful tool for comparing arthroplasty interventions, it suspends reality in terms of natural variability, drift and chaos of gait[428-430]. There is evidence that treadmill walking is associated with smaller backwards shear force and reduced knee flexor moments compared to overground walking [421, 423, 431].

The treadmill may be used in conjunction with a hand safety rail and/or safety harness, meaning that testing becomes more feasible in frail or elderly patients or those with more disabling arthritis. However, to many it is an unfamiliar walking environment, the lack of standard visual stimuli can be disorientating and the subject must be allowed time to acclimatise and familiarise themselves before measurements are taken[432]. The laboratory space requirements with a treadmill are, however, a fraction of those for a traditional gait laboratory, which, together with more efficient data collection times, has reduced the cost of this investigation and enabled this technology to become accessible in specialist orthopaedic hospitals and research institutions.

The data for this thesis was collected on an h/p/cosmos Gaitway™ II treadmill (h/p/cosmos, Nussdorf, Germany, Figure 6.3). Beneath the moving belt, the treadmill has been instrumented with two tandem 60 x 60cm force plates (Kistler Instrument Corporation, Amherst, NY). The tandem arrangement enables the software to differentiate between the left and right foot and calculate temporospatial measurements (Figure 6.14). Piezoelectric sensors in the four corners of each plate sample data at a frequency of 100 per second (100Hz), converting the signal to a vertical Ground Reaction Force via patented Kistler Gaitway™ software. The treadmill was levelled and calibrated using a 10kg weight at the four corners of each force plate. The treadmill belt is 150cm in length, 50cm wide and has a maximum weight limit of 200kg. The speed ranges from 0.1-22.0 km/h in 0.1km/h increments.

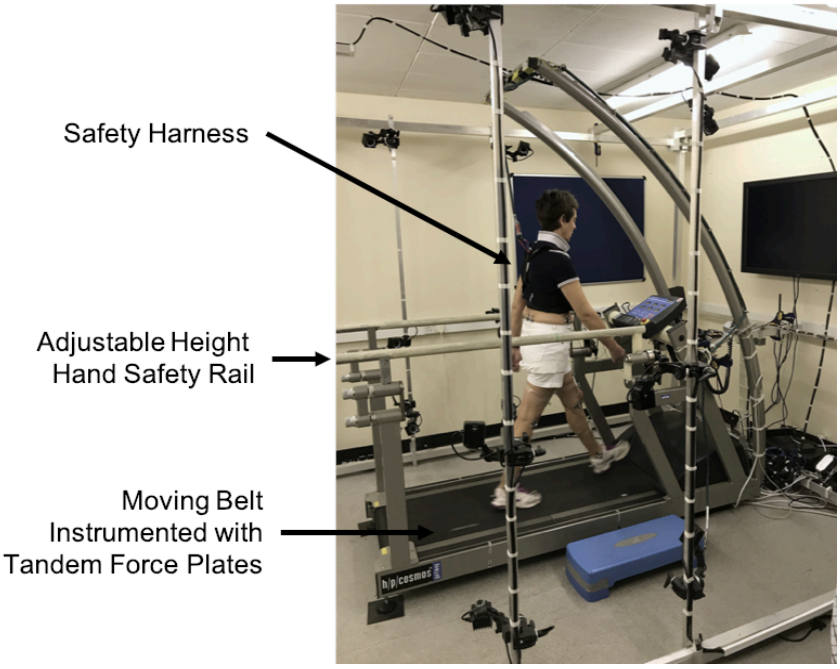


Figure 6.3. The instrumented treadmill shown with subject walking at their Top Walking Speed

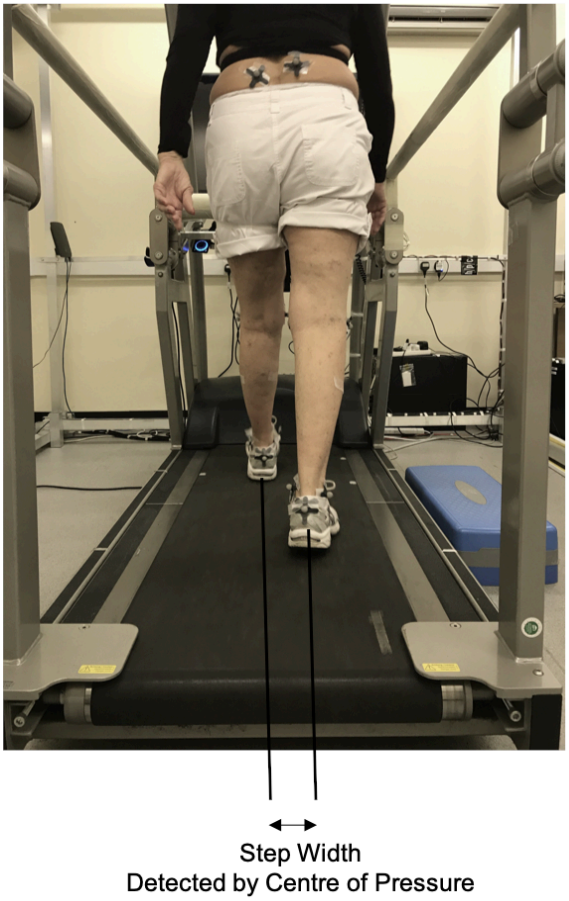


Figure 6.4. Treadmill viewed from the rear showing subject with primary medial bicompartmental arthroplasty in situ in the right leg. The centre of pressure differentiates between the right and left foot, enabling measurement of step width

6.3.1 Ground Reaction Force

Vertical and shear forces are generated as the foot makes contact with the walking surface. Their net product is reflected in quantifiable vertical ground reaction forces (GRF). For the purposes of this thesis, gait analysis is undertaken on an instrumented treadmill, with particular focus on the vertical component of GRF, though the complete action of locomotion is considerably more complex. The GRF is a vector, derived from Newton's second law [433].

$$F_y = m(a_y - g)$$

F_y	=	vertical component ground reaction force vector
m	=	rigid segment body mass
a_y	=	vertical component of acceleration of segmental body's centre of mass
g	=	acceleration of gravity (-9.81 ms^{-1})

The treadmill force plates measure the total forces acting on the body, the summation of gravitational acceleration and summated segmental accelerations. When multiple segments act on the body's mass, during walking, the equation amends to:

$$F_y = \sum_{i=1}^{n} m_i \left(a_{yi} - g\right)$$

mi	=	mass of ith segment
ayi	=	vertical acceleration of ith segment

To compare the GRF of multiple subjects, body weight (BW) must be normalised:

$$\text{BW} = \frac{GRF}{(m/g)}$$

The vertical component of GRF normalised to body weight (BW) may be plotted against percentage of contact during stance phase, to produce a typical 'M' shaped curve (Figure 6.5.) The area under the curve is the Impulse, which quantifies the magnitude of force across time. The gradient of the up-slope toward the first peak is the weight acceptance rate or loading rate. It is the change in force divided by time, determined by taking a point at 10% of the up-slope and a second at 90% and calculating the rate of rise. The maximum point of this first peak, and therefore the maximum

ground reaction force during loading, following heel-strike, is known as the Maximum Weight-Acceptance Force. Similarly, the downslope between push-off and toe-off is the unloading or push-off rate, the termination of which is where the foot leaves the ground, known as “Toe Off”.

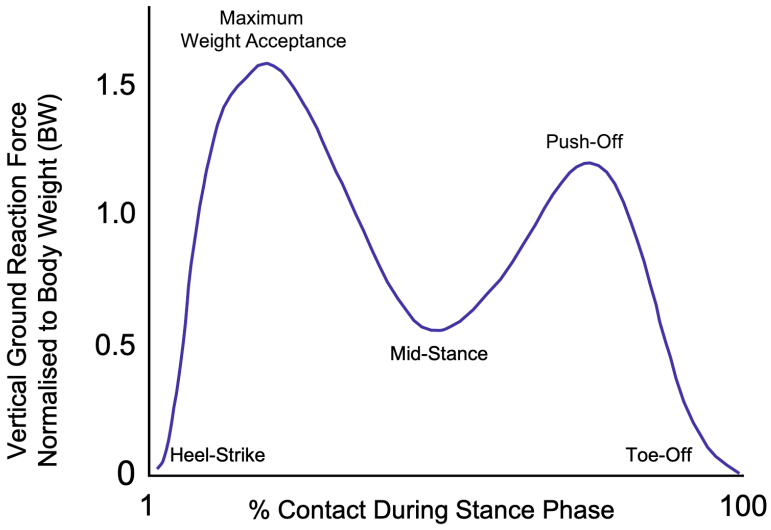


Figure 6.5. Vertical Ground Reaction Force against percentage of stance phase

GRF during weight acceptance is typically greater than body weight as the forward and downward momentum of the body is controlled by eccentric contraction of the extensor muscles (net upward force acting on the body through ground reaction). The forces sustained during the first peak are particularly relevant in the context of arthrosis, since loading in excess of body weight is associated with accelerated wear. During mid-stance, GRF falls below body weight as the centre of mass reaches its highest vertical position (lowest upward accelerations). In late stance, GRF again exceeds body weight, though this time as a result of concentric extensor muscle contractions lifting the body upwards and pushing it forward.

6.4 Rationale for Investigation of the gait of Combined Partial Knee Arthroplasty

6.4.1 Current Insights

Arthroplasty performance can be measured reliably on the instrumented treadmill, particularly during fast walking[418, 419]. Previous studies have demonstrated an advantage of UKA-M over TKA at top walking speeds[413, 418, 419]. To date only a small number of studies have investigated the functional

differences between compartmental arthroplasty and TKA, with no studies, to our knowledge, comparing CPKA to healthy controls and TKA at top walking speeds.

6.4.2 Ethical Agreement

The instrumented treadmill was first commissioned for use in the MSk Lab in 2011. Since then, over 2500 gait analysis episodes have been recorded. Patients with a range of musculoskeletal pathologies have been recruited for a number of different studies, along with healthy volunteers of all ages. Data from individual studies are anonymised and pooled into a single gait database, which is later used to sample appropriate control subjects.

Two separate ethical agreements cover the measurement of subjects on the instrumented treadmill. Both agreements give permission for collection of ground reaction forces and temporospatial measurements. The differences in the agreements relate to the use of motion capture and other parameters, which do not impact upon the data for this study.

1) Gait Analysis Using An Instrumented Treadmill. REC reference number 10/H0907/101. National Research Ethics Service. South East London Research Ethics Committee (REC) 4.

2) 3D and 2D Motion Capture Gait Analysis of Lower Limb Orthopaedic Patients. REC reference 14/SC/1243. IRAS project ID 136430. Health Research Authority NRES Committee South Central – Oxford B.

6.4.3 Power Calculations

Previous work on the instrumented treadmill compared the top walking speed of UKA-M (N = 12) to healthy controls (N = 121) and TKA (N = 12)[419]. UKA TWS was 7.9km/h, similar to healthy subjects (TWS 7.9km/h) but 37% faster than TKA TWS (5.76km/h). We assumed that the TKA subjects in our study would not differ significantly from those in the previous study, but projected that CPKA may walk up to 15% faster (TWS 6.63km/h, 15% faster). A power calculation resolved that a minimum of 14 subjects per implant group would be necessary to detect such differences with 80% power and 95% confidence.

6.6 Study Participants

6.6.1 Identification of CPKA subjects

CPKA subjects were identified from Professor Cobb's operating lists from two separate hospitals. Hospital 1 is a private hospital with available records dating from 2009–2019 whilst Hospital 2 is an NHS hospital, who were able to provide data for operations performed from 2014–2019. Since no specific operating code for any of the CPKA procedures exists, each list was manually processed by reading the listed operation(s) and the free-text for each case. All partial knee arthroplasty procedures (N = 3090) were assembled into an encrypted master database (Microsoft® Excel for Mac, Version 16). This spreadsheet formed the basis of CPKA subject identification. Patients were highlighted if they underwent:

1. More than one ipsilateral arthroplasty procedure on the same day (listed as UKA+/-PFA, or UKA+UKA, for example), identifying primary CPKA
2. Multiple ipsilateral procedures on different days, identifying revision of PKA to CPKA and / or revision to TKA
3. Bilateral procedures

A number of primary and staged CPKA subjects were identified, however, this method failed to capture certain groups:

1. PKA revised to CPKA where the primary procedure pre-dated the operating lists (pre-2009 Hospital 1, pre-2014 Hospital 2).
2. PKA revised to CPKA where the primary procedure was performed under a different surgeon.

For this reason, it became apparent that a number of CPKA subjects could not be identified from the operating lists, therefore, the pre- and post-operation radiographs of all PKAs were reviewed (in excess of 15,000 radiographs). Where CPKA were identified , the treatment pathway was noted, along with pre-operative pattern of arthrosis, graded according to Kellgren and Lawrence[434] for each compartment.

From the database, 3090 partial knee arthroplasty procedures were identified (Figure 6.6). Of these, 118 primary CPKA procedures were performed (BCA-M n= 69, BCA-L n= 34, Bi-UKA n= 15), accounting for 5% of Professor Cobb's arthroplasty practice. A further 74 (2.4%) CPKAs were performed as staged procedures.

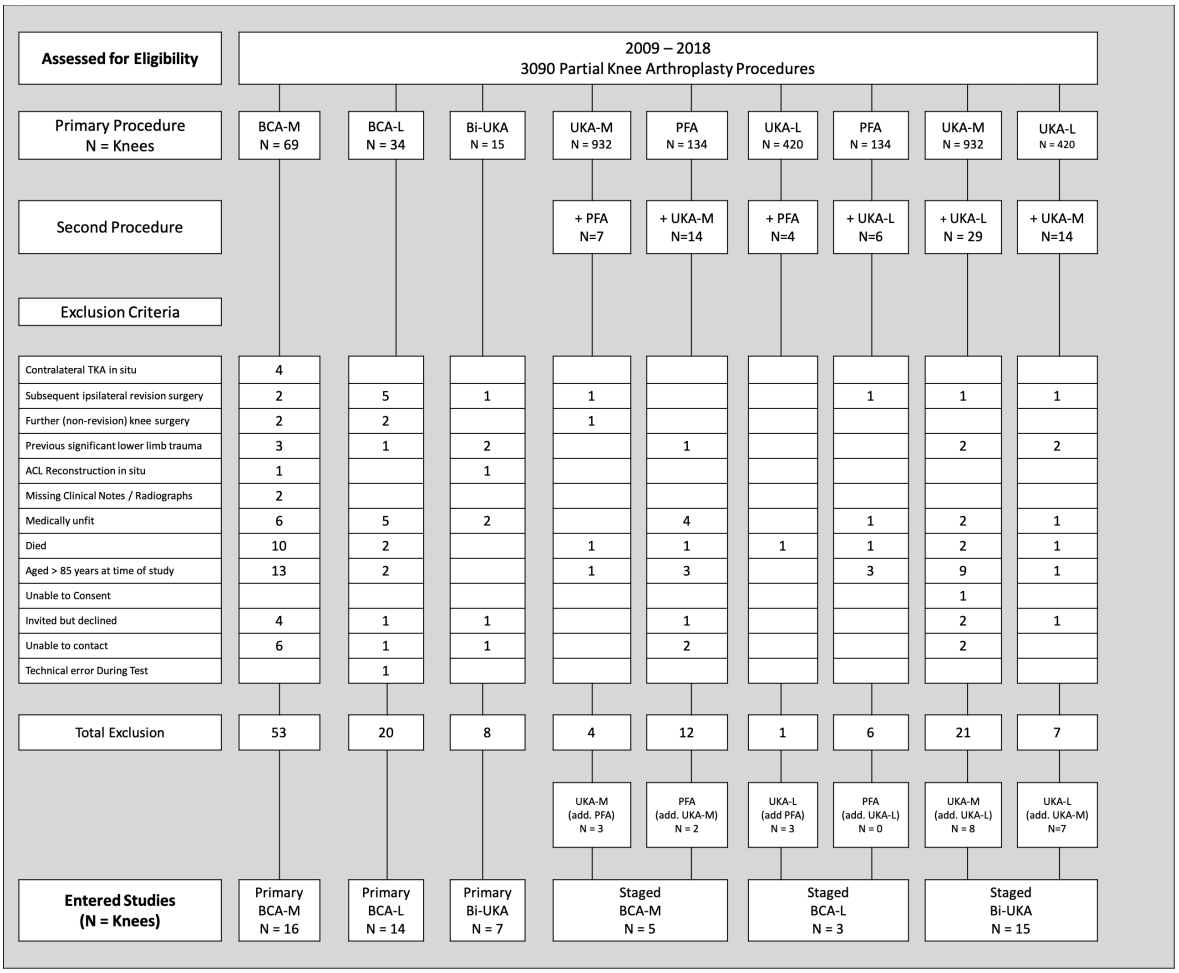


Figure 6.6. Route to entry for Combined Partial Knee Arthroplasty Subjects into the study

After exclusions, as detailed below, 37 primary and 23 staged CPKA underwent gait analysis. The primary procedures comprised of primary BCA-M (N = 16), primary BCA-L (N = 14), primary Bi-UKA (N = 7). The staged procedures were: staged BCA-M (N = 5), staged BCA-L (N = 3) and staged Bi-UKA (N = 15). Of the 37 subjects, 12 had been measured prior to the start of this PhD, none of whom had undergone motion capture, hence the decision not to include this data, though it were collected, for subsequent patients.

6.6.1.1 Excluded Subjects

Though it had been intended that all 192 CPKA knees would be included in the gait study, 132 (81 primary and 51 staged) were excluded, as detailed in Figure 6.6 and Table 6.1. A compromise was made between selection bias through the exclusion of subjects, Vs. confounding factors which may impact gait.

The ideal subjects for gait analysis are those with disease/implants confined to the joint in question, with otherwise healthy joints and no other arthroplasty implants in situ. Discounting all others results in a very narrow pool and would have excluded a significant number of CPKA patients. However, including them introduces error and uncertainty about the accuracy of the results and/or the conclusions. Previous gait studies suggested that UKA-M subjects have a near-normal gait, while TKA gait is significantly different[413, 418, 419]. For this reason, it was felt that an acceptable compromise would be to include CPKA subjects with a contralateral PKA in situ, but exclude those with a contralateral TKA (n= 4 primary BCA-M). There is some evidence that ACL reconstruction has an impact on vertical Ground Reaction Forces[435, 436], therefore, CPKA subjects whom had an ACL graft in situ (n=2), were excluded from the study. Similarly, patients with significant previous lower limb trauma were excluded. Subjects were excluded if they had undergone further ipsilateral surgery, be that revision of the CPKA or further surgery around the knee, even if the prosthesis were retained (Table 6.1.)

Medical reasons for exclusion focused on safety to undertake intensive exercise on the treadmill, hence those with significant cardiovascular or respiratory conditions were excluded. A small number of patients were unfortunately undergoing cancer treatment or had neurological conditions including Parkinson's disease affecting balance and gait. One patient had developed dementia.

6.6.1.1.1 Revision Rates of Combined Partial Knee Arthroplasty within the overall Cohort

Though not the subject of this study, it is noted that the revision rates in the entire CPKA cohorts are as follows: Primary BCA-M 2/69 (2.9%), Primary BCA-L 5/34 (14.7%), Primary Bi-UKA 1/15 (6.7%), staged BCA-M 1/21 (4.8%), staged BCA-L 1/10 (10%), staged Bi-UKA 2/43(4.7%). However, relative to registry data, this cohort data is small, so the numbers are interpreted with caution.

Reason For Exclusion	CPKA	Type	N=	Further Details	RPKC
Subsequent Ipsilateral Revision Surgery	BCA-M	Primary	1	Conversion to Tricompartmental Arthroplasty after 5yrs	PR2b
			1	Revision to TKA after 7 months (another centre)	PR3
	BCA-M	Staged	1	Conversion to Tricompartmental Arthroplasty after 7yrs	PR2b
	BCA-L	Primary	1	Exchange of patellar button for loosening after 1 year	PR1
			1	Revision of UKA-L baseplate from mobile to fixed bearing after 1 year	PR2a
			1	Conversion to Tricompartmental Arthroplasty after 5 months	PR2b
			1	Revision to TKA after 1 year (another centre)	PR3
			1	Revision to TKA after 6 years (another centre)	PR3
	BCA-L	Staged	1	Revision to TKA after 6yrs	PR3
	Bi-UKA	Primary	1	Conversion to Tricompartmental Arthroplasty after 5yrs	PR2b
	Bi-UKA	Staged	1	Conversion to Tricompartmental Arthroplasty after 2yrs	PR2b
			1	Conversion to Tricompartmental Arthroplasty after 2yrs	PR2b
Further (non-revision) knee surgery	BCA-M	Primary	1	Medial Patellofemoral Ligament Reconstruction	PR1
			1	Open Reduction Internal Fixation Proximal Tibia for peri-prosthetic fracture	N/A
	BCA-M	Staged	1	Medial Patellofemoral Ligament Reconstruction	PR1
	BCA-L	Primary	1	Quadriceps tendon repair - implants retained	PR1
			1	Multiple arthroscopic washouts for infection	N/A

Table 6.1. Reasons for Exclusion of combined partial knee arthroplasty subjects from the gait analysis study

6.6.1.2 Matching to Healthy Subjects

For each study, the CPKA group demographics were noted. Healthy controls from the prospectively collected gait database were matched in SPSS® (Version 27, IBM®) according to sex, body mass index and age at the time of gait assessment. Healthy subject data were analysed for the right leg only.

6.6.1.3 Matching to Posterior-Cruciate Retaining Total Knee Arthroplasty

Three senior surgeons have contributed TKA subjects to the prospectively collected gait database, since its inception. Professor Cobb has a sub-specialist PKA practice and performs relatively few TKAs per year. Of the other two surgeons, both of whom practice at Hospital 2, one has a mixed practice of PKA and TKA (DN), whilst the third does not perform PKA procedures routinely (RS).

At the time of data analysis, 49 subjects were identified from the database as having a posterior-cruciate retaining TKA in situ, all of whom were put forward for the study (Figure 6.7). TKA subjects were excluded if they were measured pre-revision surgery (n= 5), had a ipsilateral hip replacement in situ (n= 2), significant contralateral knee OA Kellgren and Lawrence (KL) ≥ 2 on their most recent

radiographs (n= 9) or pre-operative radiographic evidence of tricompartmental KL ≥ 2 OA and/or anterior tibial translation >7mm suggestive of ACL dysfunction[314] (n=5).

The intention had been to match the pre-operative pattern of OA to that of the CPKA procedure under investigation. For example, for the BCA-M gait study, the desire was to use only those TKAs whom pre-operatively had medial with patellofemoral OA and an intact ACL. Similarly, for the Bi-UKA study it was preferred that only TKA subjects with medial and lateral compartment OA but an intact patellofemoral compartment were included. However, of those subjects who had been prospectively measured on the treadmill, numbers of TKA subjects matching the required disease patterns were too small to reach statistical power: of those eventually entering the study, 17 subjects had single compartment disease (medial OA n=13, lateral OA n=4), eight had medial and lateral OA, two had medial with patellofemoral OA and only one had lateral with patellofemoral OA. Significant time constraints did not allow for the recruitment of further patients for the TKA control group. Hence, a decision was made to exclude all TKA subjects with pre-operative evidence of tricompartmental OA, ACL dysfunction or those measured immediately prior to further surgery. In study 2 (primary BCA-M) TKA subjects whom had not undergone patella resurfacing were excluded, since all BCA-M subjects had resurfaced patellae. In study 4 (primary and staged Bi-UKA) and study 5 (staged Bi-UKA), TKA subjects with pre-operative patellofemoral OA KL ≥ 2 were excluded, given that the Bi-UKA subjects had intact patellofemoral compartments. Failure to match pre-operative patterns of disease is a limitation of the study and is discussed towards the end of this chapter.

In total, 28 posterior-cruciate retaining TKA patients were entered into the study and formed a 'pool' of subjects (Figure 6.7). TKAs were drawn from the pool by matching in SPSS (IBM™ V27) to the demographics of each CPKA study group. The TKA implants we not all the same. The majority of subjects were implanted with a Genesis II (n=22, Smith & Nephew) and the remainder being the P.F.C® Sigma® (n=4, De Puy Synthes) or Triathlon® CR Cemented (n=2, Styker Orthopaedics). All TKA surgery had been performed with conventional instrumentation, without the assistance of robotics or navigation. 21 subjects had undergone patellar resurfacing, whilst 7 were left native. Of the 21 subjects with resurfaced patellae, 15 had no pre-operative radiological evidence of patellofemoral OA KL ≥ 2. All subjects in the TKA group would likely have been offered a PKA or CPKA under the current practise of Professor Cobb.

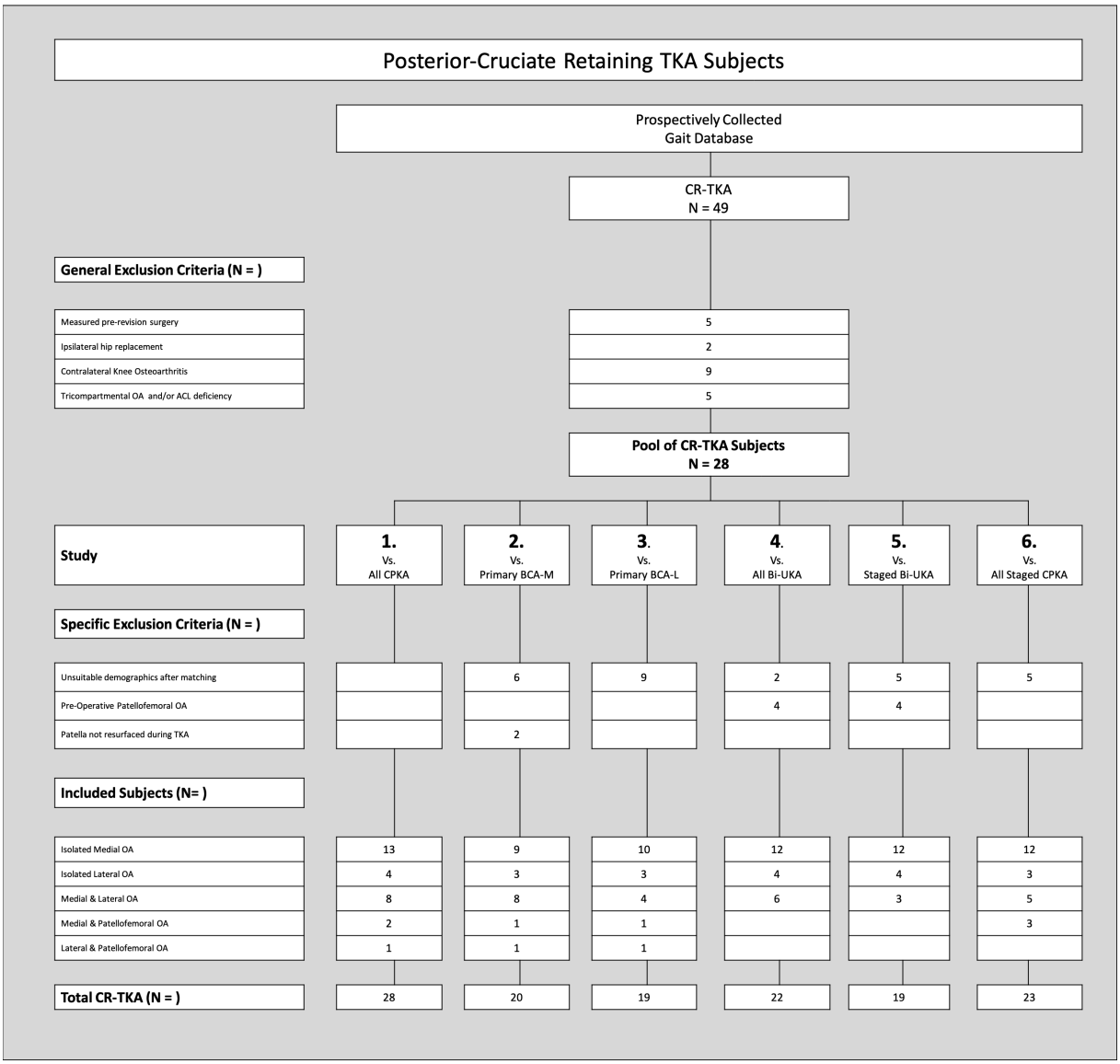


Figure 6.7. Route to entry of posterior-cruciate retaining Total Knee Arthroplasty into the studies.

6.6.2 Data Analysis

A series of studies were undertaken to investigate and understand the gait of each CPKA combination. The collected gait data has been analysed in six different studies:

1. All combined partial knee arthroplasty (primary and staged)
2. Primary medial bicompartmental arthroplasty
3. Primary lateral bicompartmental arthroplasty
4. All Bi-Unicondylar Arthroplasty (primary and staged)
5. Staged Bi-Unicondylar arthroplasty
6. Staged Combined Partial Knee Arthroplasty

6.6.3 Test Protocol

Earlier work had determined that walking at 4km/h for two minutes was sufficient for acclimatisation to the treadmill, and that minimum increments of 0.5km/h were required for the subject to report differences in difficulty level[437]. Subjects walked at each new speed for 30 seconds, before data were recorded. The maximum speed at which the subject felt comfortable walking, or before they felt compelled to run, was termed the 'top walking speed' (TWS), and was used to compare GRFs and temporospatial measurements between subjects. With every 0.1m/s increase in top walking speed, life expectancy improves significantly[23] and may be considered a proxy measure for a subject's global post-operative health[317, 418, 419 438]. As physical demands increase, differences between implant groups become more apparent[191, 439, 440]. Consequently, TWS was selected as the comparator in order to specifically characterise the upper limits of performance, differentiate implant characteristics and make comparisons to healthy gait more meaningful. Subjects walked, on average, for 12 minutes continuously in soft-soled sports shoes. Use of the hand safety rail was discouraged, except during the warm up and acclimatisation phase. Any tests recorded where the subject made contact with the safety rail were discarded and the trial repeated. If the subject was unable to complete the test without use of the safety rail, the test was stopped and the fastest speed where data were collected without contact with the hand safety rail, was the speed used for analysis. At the time of data collection, the subject's age, height, weight and leg length (greater trochanter to medial malleolus) were recorded in order to normalise the data for body weight and leg length[416].

6.7 Statistical Analysis

Output data from the Kistler Gaitway™ software were averaged using a custom MathWorks® MATLAB® script which was modified for this study to automate normalisation for leg length and creation of force graphs at top walking speeds. Averaged data were analysed in IBM® SPSS® Version 27 to compare subjects. The Shapiro-Wilk test demonstrated that a number of gait variables were not normally distributed, therefore, all variables between implant groups were compared using Kruskal-Wallis, then Mann-Whitney Test with Bonferroni Correction. Significance was set at $\alpha = 0.05$.

6.8 Results

6.8.1 The Gait of Combined Partial Knee Arthroplasty

Study 1 included all 60 CPKA subjects identified in Figure 6.6. Although a heterogenous group in terms of implant configuration, in the practise of the majority of surgeons across the world, these patients would almost certainly all have undergone TKA for their pattern of disease. Therefore, assessing them *en masse* as an "alternative to TKA" group sets the stage for further sub-group analysis.

6.8.1.1 Subjects and Controls

All 60 CPKA subjects were compared to healthy controls (n = 22) and TKA subjects (n = 28) as previously described (Figure 6.6, Table 6.2). Of the TKA subjects, 17 had isolated single-compartment OA (medial n = 13, lateral n = 4) while 11 had two-compartment disease (medial and lateral n = 8, medial and patellofemoral n = 2, lateral and patellofemoral n = 1. (Figure 6.7). The subjects were matched for sex, age, body mass index, and height (Table 6.2). The arthroplasty groups were matched for median months post-surgery (CPKA 12.5 Vs TKA 18.5, p=0.2), however, there was discrepancy in terms of mean months post-surgery (CPKA 19 ± 17months, TKA 46 ± 48months, p=<0.001).

Subject	Healthy	All CPKA	TKA	P value
Number of Knees (N =)	22	60	28	
Sex: M:F (% male)	10 : 12 (45%)	22 : 38 (37%)	12 : 16 (43%)	0.7
Age (Years)	64 ± 7.7	67 ± 10.0	67 ± 9	0.4
Body Mass Index (kg/m^2)	26.8 ± 5.4	27.2 ± 4.8	27.4 ± 4.1	0.9
Height (cm)	170 ± 9	172 ± 7	172 ± 11	0.6
Mean Months Post-Surgery (SD)		19 ± 17	46 ± 48	<0.001
Median Months Post-Surgery (Range)		12.5 (4 – 81)	18.5 (6 – 150)	0.2

Table 6.2. Demographics of the groups included in study 1: all primary and staged combined partial knee arthroplasty (CPKA) subjects compared to healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA). All values are means with standard deviation unless otherwise specified. Sex and median months post-surgery are each compared with a Chi-Square test. All other demographics are compared with ANOVA.

6.8.1.2 Top Walking Speeds

Both arthroplasty groups were slower than healthy controls (Table 6.3). CPKA were 12% slower ($p<0.001$) while TKA were 24% slower ($p<0.001$). CPKA were 16% faster than TKA ($p<0.001$). The differences in top walking speed remained the case after correcting for leg length (all Hof Speeds $p<0.001$).

Subject	Healthy Controls	CPKA (all subjects)	TKA
Top Walking Speed (km/h)	7.2 ± 0.7	6.4 ± 0.9 [a, b]	5.5 ± 0.7 [a, b]
Hof Speed (H)	0.73 ± 0.1	0.64 ± 0.1 [a, b]	0.56 ± 0.1 [a, b]
Weight Acceptance Rate (BW/s)	10.8 ± 3.5	9.7 ± 3.5	8.1 ± 3.7
Maximum Weight Acceptance Force (BW)	1.6 ± 0.2	1.4 ± 0.2 [a, b]	1.3 ± 0.2 [a, b]
Mid-Stance Force (BW)	0.5 ± 0.1	0.6 ± 0.1 [a, b]	0.7 ± 0.1 [a, b]
Push-Off Force (BW)	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.1
Push-Off Rate (BW/s)	4.1 ± 0.9	3.8 ± 0.9	3.8 ± 0.8
Step Length (cm)	82 ± 8	79 ± 8 [b]	71 ± 8 [a, b]
Stride Length (cm)	165 ± 16	158 ± 17 [b]	145 ± 17 [a, b]
Step Width (cm)	12 ± 3	13 ± 3	14 ± 3
Cadence (Step/min)	60 ± 5.2	56 ± 5.3 [a, b]	53 ± 4.7 [a, b]
Impulse (BW/s)	387 ± 23	377 ± 24	380 ± 26
Double Support Time (s)	0.28 ± 0.05	0.30 ± 0.07 [b]	0.34 ± 0.07 [a, b]
Gait Cycle Time (s)	2.0 ± 0.2	2.1 ± 0.2 [a, b]	2.3 ± 0.2 [a, b]
Contact Time (s)	1.3 ± 0.1	1.4 ± 0.2 [b]	1.5 ± 0.1 [a, b]

Table 6.3. Gait characteristics at top walking speeds. Indicated values are means ± standard deviation. BW = normalized to body weight. All variables subject to Kruskal-Wallis then Mann-Whitney U with Bonferroni Correction. Significant differences ($p<0.05$) between groups annotated with superscript: [a] implant group compared to healthy control, [b] implant groups compared to each other. Where no superscript is noted, $p>0.05$

Median CPKA TWS were 6.5 km/h (IQR 5.5 – 7.0km/h), 0.75 km/h slower than healthy subjects median 7.25 km/h (IQR 6.6 – 8.0km/h) but 1km/h faster than TKA (median 5.5 km/h, IQR 5.0-6.0km/h). Of the CPKA subgroups, there was an even distribution of TWS amongst primary and staged BCA-M; BCA-L and Bi-UKA (Figure 6.8).

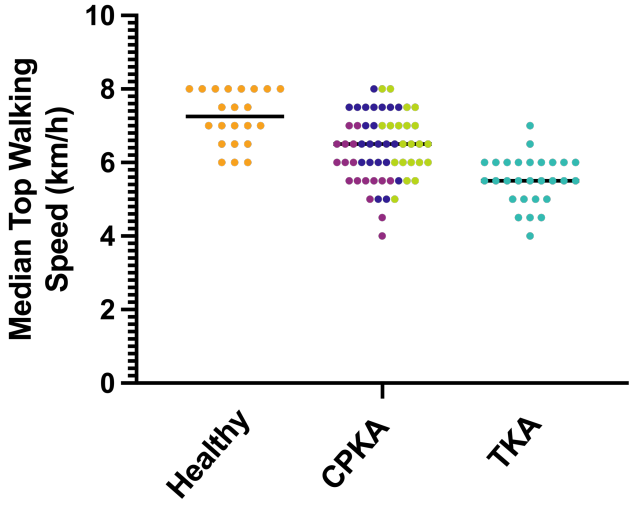


Figure 6.8 Median Top Walking Speed (km/h) for subjects in study 1: combined partial knee arthroplasty (CPKA) compared to healthy subjects and posterior-cruciate retaining total knee arthroplasty (TKA). Of the CPKA group, the individual procedures are depicted: medial bicompartmental arthroplasty (green), lateral bicompartmental arthroplasty (light purple), bi-unicondylar arthroplasty (dark purple).

6.8.1.3 Vertical Ground Reaction Forces

Both CPKA and TKA groups had reduced weight acceptance rate compared to healthy subjects. Neither reached statistical significance, although TKA approached it (CPKA Vs healthy $p>0.8$, TKA Vs Healthy $p=0.054$, Table 6.3 Figure 6.9). TKA measured the lowest maximum weight acceptance force, 20% lower than healthy subjects ($p<0.001$) and 8% lower than CPKA ($p=0.009$). CPKA were also slower than healthy subjects (13%, $p<0.001$) but closer to healthy weight acceptance force than TKA. TKA measured the highest mid-stance force compared to healthy subjects ($p<0.001$) and CPKA ($p<0.012$). Relative to TKA, CPKA were closer to healthy subjects in terms of mid-stance force, but still significantly higher ($p<0.001$). All groups were similar at push off ($p=1$).

CPKA had significantly reduced cadence compared to healthy subjects ($p<0.02$, Table 6.3) and increased gait cycle time ($p<0.02$) but other temporospatial differences did not reach significance (all $p>0.15$). TKA had the lowest cadence relative to healthy subjects ($p<0.001$) and CPKA ($p<0.02$), and longer double support, gait cycle and contact times than healthy and CPKA subjects (all $p<0.02$).

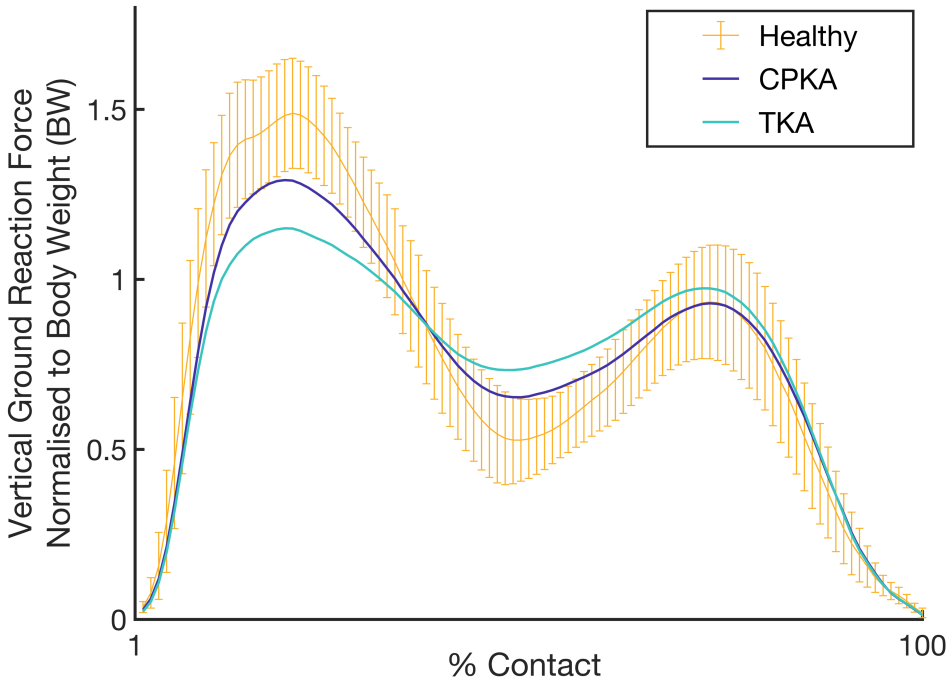


Figure 6.9. Vertical Ground Reaction Forces during stance phase of gait for all subjects with combined partial knee arthroplasty (CPKA) compared to primary posterior-cruciate retaining total knee arthroplasty (TKA), normal range for healthy subjects shown with 95% confidence intervals.

6.8.1.4 Step and Stride Lengths

Both arthroplasty groups had shorter step and stride lengths than healthy subjects. CPKA measured mean 3cm (4%) shorter step lengths, though this did not reach significance (p=0.6). TKA were mean 11cm (13%) shorter in step length than healthy subjects (p<0.001). CPKA had mean 8cm (11%) longer step lengths than TKA (p<0.001, Table 6.3).

CPKA median step length were 79cm (IQR 73 – 85cm,Figure 6.10), while healthy controls measured median 82cm (IQR 77 – 88cm). TKA measured shorter step lengths, median 71cm (IQR 67 – 76cm). Informal subgroup analysis suggests that whilst BCA-M and Bi-UKA had a wider range of step lengths (BCA-M median 82cm, IQR 74 – 87cm, Bi-UKA median 80cm, IQR 76 – 85 cm), BCA-L had predominantly shorter steps (median 72, IQR 70-78), despite being corrected for leg length (Figure 6.10).

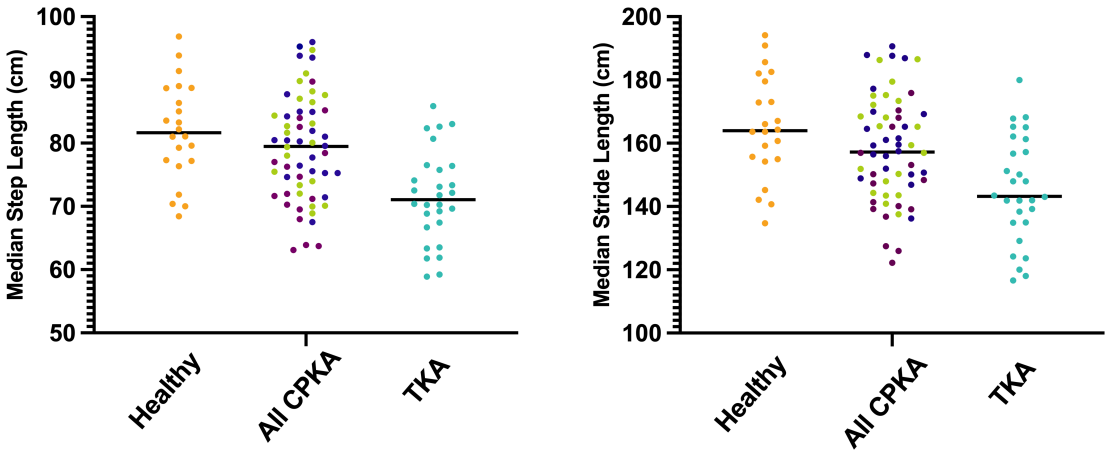


Figure 6.10. Median step and stride lengths for all combined partial knee arthroplasty (All CPKA) subjects compared to matched healthy subjects and posterior-cruciate retaining total knee arthroplasty subjects (TKA). CPKA shown with the combined simultaneous and staged subgroups of medial bicompartmental arthroplasty (green), lateral bicompartmental arthroplasty (light purple) and bi-unicondylar arthroplasty (dark purple).

Differences in step length translated into differences in stride length (Table 6.3). CPKA had a 7cm (4%) shorter mean stride length than healthy subjects (p=0.4) but 13cm (9%) longer than TKA (p=0.006). TKA had the shortest mean stride lengths, 20cm (12%) shorter than healthy subjects (p=0.003).

CPKA median stride length were 157cm (IQR 147 – 169, Figure 6.10), 7cm shorter than healthy subjects, median 164cm (IQR 155 – 178cm), but 14cm longer than TKA, median 143cm (IQR 135 – 158cm). Of the CPKA subgroups, BCA-M had the longest median stride length at 165cm (IQR 148 – 173cm), Bi-UKA were 6cm shorter at 159cm (IQR 152 – 170cm). BCA-L were the shortest, median 147cm (IQR 139 – 157cm), though still 4cm longer than TKA.

6.10 The Gait of Primary Medial Bicompartmental Arthroplasty

6.10.1 Publication

This section includes text and images from the following publication, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. Medial bicompartmental arthroplasty patients display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients. Knee Surg Sports Traumatol Arthrosc. 2021 Oct 23. doi: 10.1007/s00167-021-06773-8

6.10.2 Patients

Of 3090 knee arthroplasty procedures, 69 patients had undergone primary modular BCA-M. After 53 exclusions (Figure 6.6, Table 6.1), 16 BCA-M patients entered study 2. BCA-M matched to 19 healthy control subjects and 20 TKA patients (Figure 6.7, Table 6.4). Of the TKAs, 11 had single compartment disease (medial n = 8, lateral n=3). The remaining had two-compartment disease (medial and lateral n=8, lateral with patellofemoral n=1).

6.10.3 Results

TKAs were mean 40.6 $\pm$ 43 months post-surgery, 19.6 months longer than primary BCA-M (21 $\pm$ 18) though this did not reach statistical significance (p=0.1). The median months post-surgery were BCA-M 12.5 months (range 6-65 months) compared to TKA, 19.5 months (range 6-147 months, p=0.5, Table 6.4).

Subject	Healthy	Primary BCA-M	TKA	P value
Number of Knees (N =)	19	16	20	
Sex: M:F (% Male)	7 : 12 (37%)	6 : 10 (38%)	7 : 13 (35%)	1
Age (Years)	63 ± 9.7	68 ± 8.1	65 ± 9.9	0.3
Body Mass Index (kg/m^2)	26.6 ± 4.7	26.9 ± 5.1	27.2 ± 3.9	0.9
Height (cm)	171 ± 10	175 ± 8	171 ± 12	0.5
Mean Months Post-Surgery		21 ± 18	40.6 ± 43	0.1
Median Months Post-Surgery (Range)		12.5 (6 – 65)	19.5 (6 – 147)	0.5

Table 6.4 Demographics of the groups included in study 2: primary medial bicompartmental arthroplasty (BCA-M) subjects compared to healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA). All values are means with standard deviation unless otherwise specified. Sex and median months post-surgery are each compared with a Chi-Square test. All other demographics are compared with ANOVA.

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6.10.4 Top Walking Speeds

Objectively, the medial bicompartmental arthroplasty top walking speed of 6.7 ± 0.8 km/h were 0.5 km/h (7%) slower than healthy controls (p=0.16, Table 6.5, Figure 6.11) but 1.3 km/h (24%) faster than total knee arthroplasty subjects (5.4±0.6 km/h, p<0.001). The TKA group walked 25% slower than healthy subjects (p<0.001). The differences remained apparent after Hof scaling for leg length (Table 6.5)

Subject	Healthy	Primary BCA-M	TKA
Top Walking Speed (km/h)	7.2 ± 0.7	6.7 ± 0.8 [b]	5.4 ± 0.6 [a, b]
Hof Speed (H)	0.73 ± 0.1	0.67 ± 0.1 [b]	0.54 ± 0.1 [a, b]
Weight Acceptance Rate (BW/s)	10.2 ± 3.3	9.0 ± 3.0	7.5 ± 3.3
Maximum Weight Acceptance Force (BW)	1.6 ± 0.2	1.4 ± 0.2 [b]	1.2 ± 0.1 [a, b]
Mid-Stance Force (BW)	0.5 ± 0.1	0.6 ± 0.2 [a,b]	0.7 ± 0.1 [a, b]
Push-Off Force (BW)	1.0 ± 0.1	1.0 ± 0.1	1.0 ± 0.1
Push-Off Rate (BW/s)	4.0 ± 0.9	3.8 ± 1.0	3.8 ± 0.8
Step Length (cm)	82 ± 8	82 ± 8 [b]	71 ± 7 [a, b]
Stride Length (cm)	165 ± 17	164 ± 15 [b]	144 ± 17 [a,b]
Gait Width (cm)	12 ± 3	12 ± 3	14 ± 3
Cadence (Step/min)	59.8 ± 4.9	58 ± 4.4 [b]	52 ± 4.4 [a,b]
Impulse (BW/s)	382 ± 23	379 ± 30	385 ± 25
Double Support Time (s)	0.29 ± 0.05	0.27 ± 0.05 [b]	0.34 ± 0.08 [b]
Gait Cycle Time (s)	2.0 ± 0.2	2.1 ± 0.2 [b]	2.3 ± 0.2 [a,b]
Contact Time (s)	1.3 ± 0.1	1.31 ± 0.2 [b]	1.50 ± 0.2 [a,b]

Table 6.5. Gait characteristics at top walking speeds. Values are means ± standard deviation. BW = normalized to body weight. All variables subject to Kruskal-Wallis then Mann-Whitney U with Bonferroni Correction. Significance p<0.05 between groups annotated with superscript: [a] implant group Vs. healthy control, [b] implant groups Vs. each other. Where no superscript is noted, p>0.05.

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Median primary BCA-M TWS were 6.5 km/h (IQR 6.0-7.1 km/h), 1 km/h slower than healthy subjects (median 7.5 km/h, IQR 6.8 – 8.0 km/h) but 1 km/h faster than TKA (median 5.5 km/h, IQR 5.0 – 5.6 km/h, Figure 6.11).

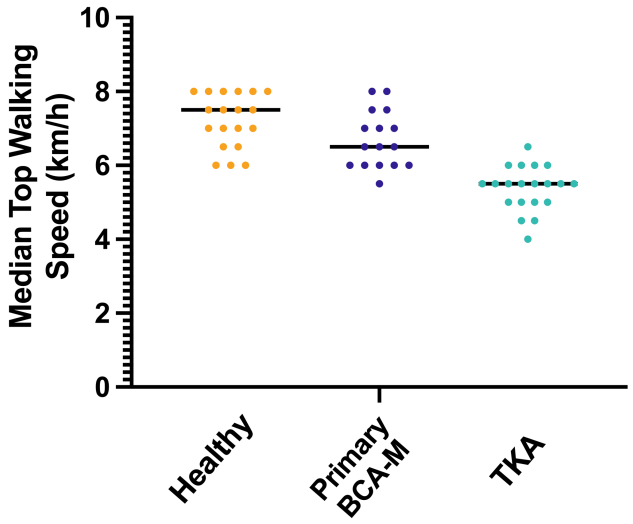


Figure 6.11. Median top walking speed (km/h) for subjects in study 2: primary medial bicompartmental arthroplasty (BCA-M) compared to healthy subjects and posterior-cruciate retaining total knee arthroplasty (TKA).

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6.10.5 Vertical Ground Reaction Forces

At top walking speeds, compared to healthy subjects, both arthroplasty groups recorded reduced weight-acceptance, though the differences did not reach significance ($p>0.06$, Table 6.5, Figure 6.12). BCA-M and healthy subjects recorded similar maximum weight acceptance force ($p=0.051$) whilst TKA were reduced ($p<0.001$). During mid-stance, both groups recorded higher forces than the healthy cohort ($p<0.03$), however, BCA-M were nearer-normal, with a significant advantage over TKA ($p<0.03$). All groups were similar in terms of push off force and rate ($p=1$). Compared to healthy and BCA-M subjects, TKA recorded reduced cadence ($p<0.003$, Table 6.5) increased double support time (Vs BCA-M $p=0.03$) increased gait cycle time ($p<0.001$) and contact time ($p<0.003$). BCA-M displayed nearer-normal temporospatial characteristics, with differences failing to reach significance when compared to healthy controls.

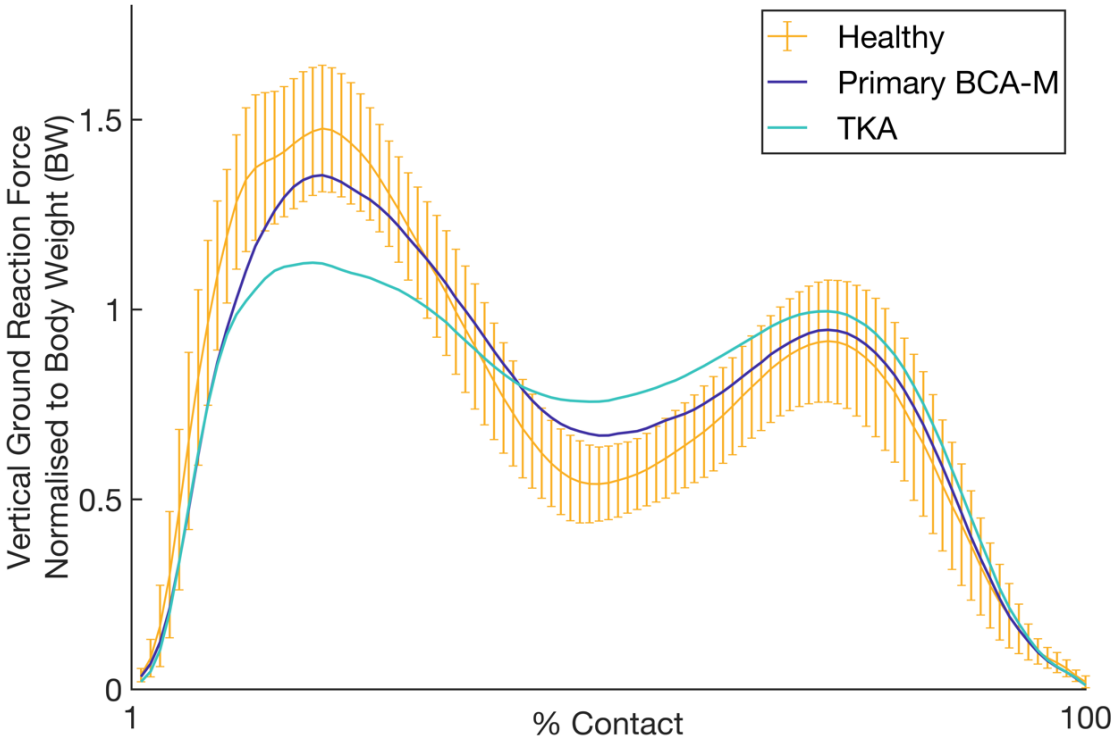


Figure 6.12. Vertical ground reaction forces during stance phase for subjects with primary medial bicompartmental arthroplasty (BCA-M) compared to primary posterior-cruciate retaining total knee arthroplasty (TKA), normal range for healthy subjects shown with 95% confidence intervals.

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6.10.6 Step and Stride Lengths

The mean BCA-M step length of 82 ± 8cm equalled that of healthy subjects (p = 1, Table 6.5). Both were 15% longer than TKA, mean 71 ± 7cm (p<0.001). Similar differences were seen with mean stride length, whereby BCA-M were just 1cm shorter than healthy subjects (BCA-M 164 ± 15cm, p=1), 14% longer than TKA (mean 144 ± 17cm, p=0.006). BCA-M median step length were similar to healthy subjects (both 82cm, IQR Healthy 77-88cm, BCA-M 75 -87cm, p=1, Table 6.5), whilst TKA were median 70cm (IQR 66-74cm) 12cm (15%) shorter (Figure 6.13). This reflected the differences in stride length, whereby, median BCA-M stride length were 167cm (IQR 150-175cm), 3cm (2%) longer than healthy subjects, while TKA stride length were median 142cm (IQR 133-158cm), 22cm (13%) shorter than healthy subjects (Figure 6.13).

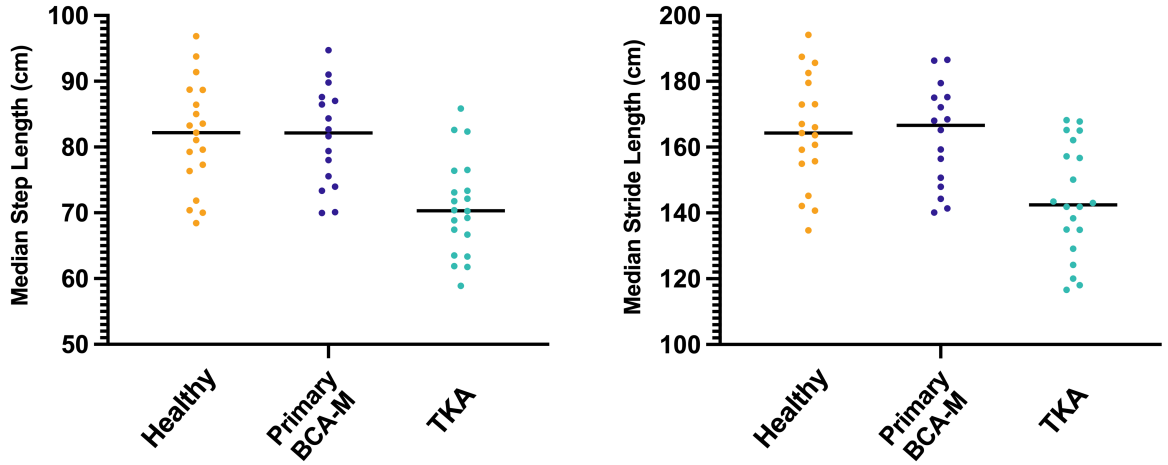


Figure 6.13. Median step length (left) and stride length (Right) for primary medial bicompartmental arthroplasty (BCA-M) compared to matched healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA)

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6.11 The Gait of Lateral Bicompartmental Arthroplasty

Study 3 investigated primary BCA-L. Of the 3090 PKA procedures, 34 were primary BCA-L, 20 BCA-L were excluded (as detailed in Figure 6.6 and Table 6.1). Consequently, the study included 14 primary BCA-L knees from 11 subjects Three female subjects underwent bilateral BCA-L, performed on the same day. Each knee was analysed individually. Comparisons were made with 15 healthy and 19 TKA subjects (Table 6.6). Compared to the other subgroup studies, this study included a disproportionately high ratio of females to males in the BCA-L group. Although differences did not reach statistical significance, the ratio of males to females in the TKA group were higher.

Of the TKA subjects, 13 had single-compartment OA (medial N = 10, lateral N = 3), while 6 s had two-compartment disease (medial with lateral N = 4, medial with patellofemoral N = 1, lateral with patellofemoral N = 1, Figure 6.7).

The mean months post-surgery for the arthroplasty groups was significantly different (BCA-L 10.6 $\pm$ 5 months, Vs. TKA 41.9 $\pm$ 49 months, p=0.03, Table 6.6). The median differences were less (BCA-M 9 months, range 5 – 23 months Vs. TKA 13 months, range 6-150 months, p=0.4).

Subject	Healthy	Primary BCA-L	TKA	P value
Number of Subjects (N =)	15	11	19	
Number of Knees (N =)	15	14*	19	
Sex: M:F (% male knees)	2 : 13 (13%)	1 : 13 (7%)	6 : 13 (32%)	0.2
Age (Years)	63 $\pm$ 9	69 $\pm$ 8	68 $\pm$ 10	0.1
Body Mass Index (kg/m^2)	27.6 $\pm$ 6	25.9 $\pm$ 4	28.0 $\pm$ 4	0.4
Height (cm)	168 $\pm$ 10	168 $\pm$ 6	170 $\pm$ 11	0.9
Mean Months Post-Surgery		10.6 $\pm$ 5	41.9 $\pm$ 49	0.03
Median Months Post-Surgery (Range)		9 (5 – 23)	13 (6 – 150)	0.4

Table 6.6. Demographics of the groups included in study 3: primary lateral bicompartmental arthroplasty (BCA-L) subjects compared to healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA). All values are means with standard deviation unless otherwise specified. Sex and median months post-surgery are each compared with a Chi-Square test. All other demographics are compared with ANOVA. *three subjects underwent bilateral BCA-L procedures.

6.11.1 Top Walking Speeds

Both arthroplasty groups walked slower than their matched healthy counterparts (Table 6.7). The BCA-L group were mean 1.5 km/h (21%) slower (p<0.001), while the TKA were 2 km/h (27%) slower

(p=0.001). These differences remained the case when corrected for leg length (p<0.001). BCA-M were 0.5 km/h (9%) faster than TKA though this did not reach significance (p=0.2), including when corrected for leg length (p>0.4).

Subject	Healthy	Primary BCA-L	TKA
Top Walking Speed (km/h)	7.3 ± 0.8	5.8 ± 0.8 [a]	5.3 ± 0.6 [a]
Hof Speed (H)	0.74 ± 0.08	0.59 ± 0.08 [a]	0.54 ± 0.07 [a]
Weight Acceptance Rate (BW/s)	10.0 ± 2.8	8.5 ± 2.9	7.0 ± 3.2 [a]
Maximum Weight Acceptance Force (BW)	1.5 ± 0.2	1.3 ± 0.2 [a]	1.2 ± 0.1 [a]
Mid-Stance Force (BW)	0.5 ± 0.1	0.6 ± 0.1 [a]	0.7 ± 0.1 [a]
Push-Off Force (BW)	1.0 ± 0.2	0.9 ± 0.1	1.0 ± 0.1
Push-Off Rate (BW/s)	4.1 ± 1.0	3.6 ± 0.8	3.6 ± 0.8
Step Length (cm)	81 ± 7	74 ± 7	69 ± 5 [a]
Stride Length (cm)	163 ± 15	147 ± 15 [a]	142 ± 15 [a]
Step Width (cm)	11 ± 3	13 ± 4	14 ± 4
Cadence (Step/min)	60.6 ± 5.1	53.8 ± 5.3 [a]	52.7 ± 5.4 [a]
Impulse (BW/s)	390 ± 24	275 ± 19	381 ± 23
Double Support Time (s)	0.27 ± 0.05	0.35 ± 0.09 [a]	0.36 ± 0.08 [a]
Gait Cycle Time (s)	2.0 ± 0.2	2.3 ± 0.2 [a]	2.3 ± 0.2 [a]
Contact Time (s)	1.3 ± 0.1	1.5 ± 0.2 [a]	1.5 ± 0.2 [a]

Table 6.7. Gait characteristics at top walking speeds. Indicated values are means ± standard deviation. BW = normalized to body weight. All variables subject to Kruskal-Wallis then Mann-Whitney U with Bonferroni Correction. Significant differences (p<0.05) between groups annotated with superscript: [a] implant group compared to healthy control, [b] implant groups compared to each other. Where no superscript is noted, p>0.05

Primary BCA-L had a median TWS of 5.75 km/h (IQR 5.5 – 6.4 km/h), 1.75 km/h slower than healthy subjects (median TWS 7.5km/h, IQR 6.75 – 8 km/h) and 0.25 km/h faster than TKA (median TKA TWS 5.5 km/h, IQR 5 – 5.75 km/h, Figure 6.14).

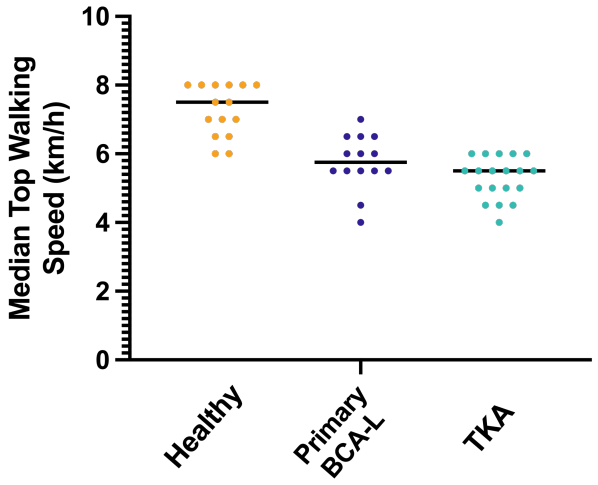


Figure 6.14. Median top walking speed (km/h) for subjects in study 3: primary lateral bicompartmental arthroplasty (BCA-L) compared to healthy subjects and posterior-cruciate retaining total knee arthroplasty (TKA).

6.11.2 Vertical Ground Reaction Forces

At top speeds, BCA-L and TKA measured lower weight acceptance rates than the healthy group. BCA-L were nearer-normal and did not reach significance (healthy Vs. BCA-L p=0.45, Table 6.7, Figure 6.15) while TKA were lower than BCA-L (p=0.42) and significantly lower than healthy subjects (p<0.001). BCA-L and TKA recorded reduced maximum weight acceptance forces, with significant differences between each of them and the healthy controls (p<0.001) but not each other (p=0.3) , though BCA-L were closer to normal. TKA recorded the highest mid-stance forces (TKA Vs Healthy p<0.001, Vs BCA-L p=0.2). BCA-L were also higher than the normal range, but not as high as TKA (BCA-L Vs Healthy p=0.04). The three groups were similar at push off (p>0.7), though the reduced push-off rates of BCA-L and TKA did not reach significance (p>0.4).

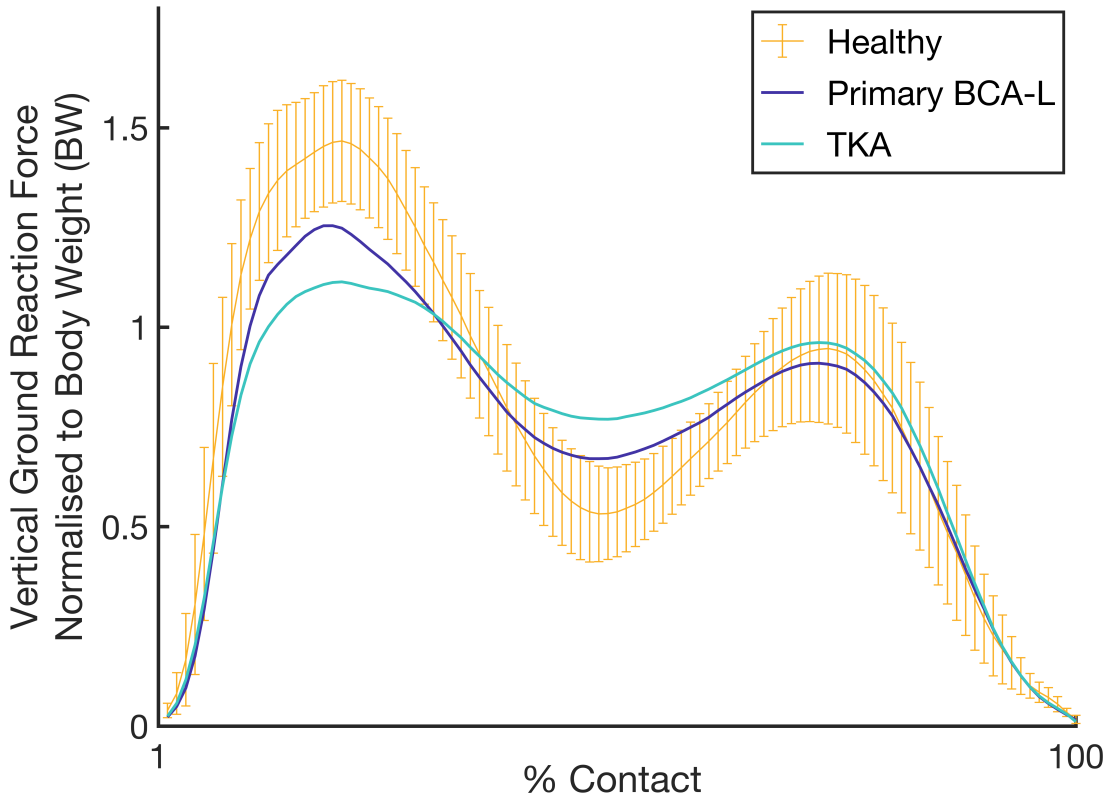


Figure 6.15. Vertical Ground Reaction Forces during stance phase of gait for subjects with lateral bicompartmental arthroplasty (BCA-L) compared to matched posterior-cruciate retaining Total Knee Arthroplasty (TKA), normal range for healthy subjects shown with 95% confidence intervals.

BCA-L and TKA had reduced cadence, increased double support, gait cycle and contact times compared to healthy subjects (Table 6.7, p<0.045) but the differences between them for these metrics were marginal (BCA-L Vs TKA p=1).

6.11.3 Step and Stride Lengths

BCA-L and TKA had shorter step and stride lengths than healthy subjects. BCA-L were mean 7cm (9%) shorter than healthy subjects (p=0.054), mean 5cm (6%) longer than TKA (p=0.2, Table 6.7). TKA were mean 12 cm (14%) shorter than healthy subjects (p<0.001). When analysed according to median lengths (Fig), BCA-L had median 3cm longer step lengths (73cm IQR 70 – 78cm) than TKA (70cm IQR 67 – 73cm). However, both groups remained significantly shorter than the step length of healthy subjects (median 82cm, IQR 77 – 86cm).

Differences in step length translated into similar differences in stride length. BCA-L were mean 16cm (10%) shorter than healthy subjects (Table 6.7) which just reached significance (p=0.045). TKA were 21cm (13%) shorter than healthy (p=0.003) and 5cm shorter than BCA-L, though this did not reach significance (p=0.08). Median healthy stride length was 164cm (IQR 155 – 173cm), 16cm longer than BCA-L (median 148cm, IQR 139 – 156cm) and 22cm longer than TKA (median 142, IQR 135 – 151cm).

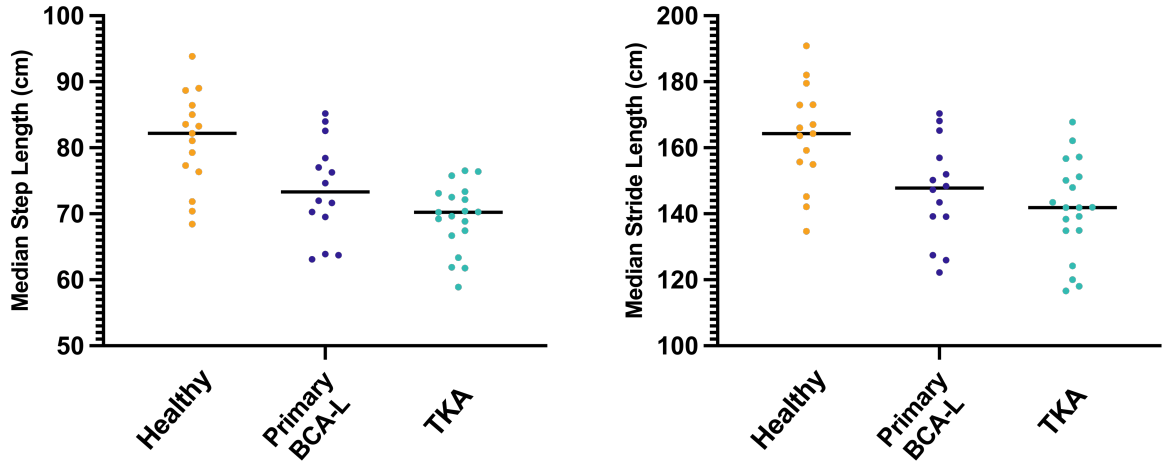


Figure 6.16. Median step length (left) and stride length (Right) for primary lateral bicompartmental arthroplasty (BCA-L) compared to matched healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA).

In summary, the gait metrics of this cohort of BCA-L and TKA subjects were suboptimal to those of matched healthy subjects. BCA-L metrics were as close or closer to normal gait compared to TKA, but the differences failed to reach significance between them, for any measured metric of gait.

6.12 The Gait of Bi-Unicondylar Arthroplasty (Primary and Staged)

6.12.1 Publication

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Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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6.12.2 Patients

In study 4, all Bi-UKA subjects were analysed collectively. After exclusions (Figure 6.6, Table 6.1), the cohort included primary Bi-UKA (n = 7) and staged Bi-UKA (n = 15). Of the staged subjects, 21 had undergone primary UKA-M, with the later addition of UKA-L, whilst 7 had undergone primary UKA-L, converted to Bi-UKA through the addition of UKA-M for progressive medial compartment disease. The control groups consisted of age- BMI- sex- and height-matched healthy subjects (n = 24) and 22 TKA subjects (Table 6.8). During matching, TKA's with evidence of PFJ KL ≥ 2 OA were excluded. Of the 22 included, 6 TKAs had KL ≥ 2 medial and lateral osteoarthritis pre-surgery, whilst 16 had OA confined to the medial (n = 12) or lateral (n = 4) compartment only (Figure 6.7).

Bi-UKA subjects were mean 23 $\pm$ 20 months post-surgery, whereas TKA were 52 $\pm$ 21 months post-surgery (p=0.02). Time points were more evenly matched when comparing median months (p=0.3, Table 6.8).

Subject	Healthy	Bi-UKA (All)	TKA	P value
Number of Knees (N =)	24	22	22	
Sex: M:F (% Male)	14:10 (58%)	14:8 (64%)	12 : 10 (55%)	0.8
Age (Years)	63 ± 8	68 ± 13	67 ± 10	0.2
Body Mass Index (kg/m^2)	27 ± 5	28 ± 5	27 ± 4	0.8
Height (cm)	173 ± 10	174 ± 8	174 ± 11	0.9
Mean Months Post-Surgery		23 ± 20	52 ± 21	**0.02**
Median Months Post-Surgery (Range)		17 (5 - 81)	24 (6-150)	0.3

Table 6.8. Demographics of the groups in study 4: Bi-Unicondylar arthroplasty () subjects compared to healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA). All values are means with standard deviation unless otherwise specified. Sex and median months post-surgery are each compared with a Chi-Square test. All other demographics are compared with ANOVA

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6.12.3 Top Walking Speeds

The Bi-UKA group walked, on average, 20% faster than primary TKA, though neither arthroplasty group walked as fast as the healthy subjects (mean top walking speed: healthy 7.4±0.7km/h, Bi-UKA 6.7±0.9km/h, TKA 5.6±0.7km/h, all p<0.001, Table 6.9). Bi-UKA subjects were 9% slower than healthy controls, while TKA were 24% slower (p<0.02). In all instances, this remained the case after correcting for leg length (Hof p<0.02).

Subject	Healthy Controls	All Bi-UKA	TKA
Top Walking Speed (km/h)	7.4 ± 0.7	6.7 ± 0.9 [a,b]	5.6 ± 0.7 [a,b]
Hof Speed (H)	0.7 ± 0.1	0.7 ± 0.1 [a,b]	0.6 ± 0.1 [a,b]
Weight Acceptance Rate (BW/s)	10.8 ± 3.5	10.5 ± 4.0	7.9 ± 3.8
Maximum Weight Acceptance Force (BW)	1.6 ± 0.2	1.4 ± 0.1 [a,b]	1.3 ± 0.2 [a,b]
Mid-Stance Force (BW)	0.5 ± 0.1	0.6 ± 0.1 [a,b]	0.7 ± 0.1 [a,b]
Push-Off Force (BW)	1.0 ± 0.2	1.0 ± 0.1	1.0 ± 0.1
Push-Off Rate (BW/s)	4.3 ± 1.0	4.0 ± 0.8	3.8 ± 0.9
Step Length (cm)	85 ± 10	82 ± 8 [b]	73 ± 7 [a,b]
Stride Length (cm)	170 ± 20	163 ± 15 [b]	150 ± 16 [a,b]
Step Width (cm)	13 ± 3	14 ± 3	13 ± 3
Cadence (Step/min)	60 ± 5	57 ± 6 [b]	52 ± 5 [a,b]
Impulse (BW/s)	385 ± 21	377 ± 23	380 ± 29
Double Support Time (s)	0.28 ± 0.1	0.29 ± 0.1 [b]	0.34 0.1 [a,b]
Gait Cycle Time (s)	2.0 ± 0.2	2.1 ± 0.2 [b]	2.3 ± 0.2 [a,b]
Contact Time (s)	1.3 ± 0.1	1.4 ± 0.1 [b]	1.5 ± 0.1 [a,b]

Table 6.9. Gait characteristics at top walking speeds. Indicated values are means ⍰ standard deviation. BW = normalized to body weight. All variables subject to Kruskal-Wallis then Mann-Whitney U with Bonferroni Correction. Significant differences (p<0.05) between groups annotated with superscript: [a] implant group compared to healthy control, [b] implant groups compared to each other. Where no superscript is noted, p>0.05

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Bi-UKA median TWS were 6.5 km/h (IQR 6 – 7.5 km/h), 1 km/h slower than healthy subjects (median TWS 7.5 km/h, IQR 7 – 8 km/h) but 1 km/h faster than TKA (median TWS 5.5km/h, IQR 5 – 6 km/h, Figure 6.17).

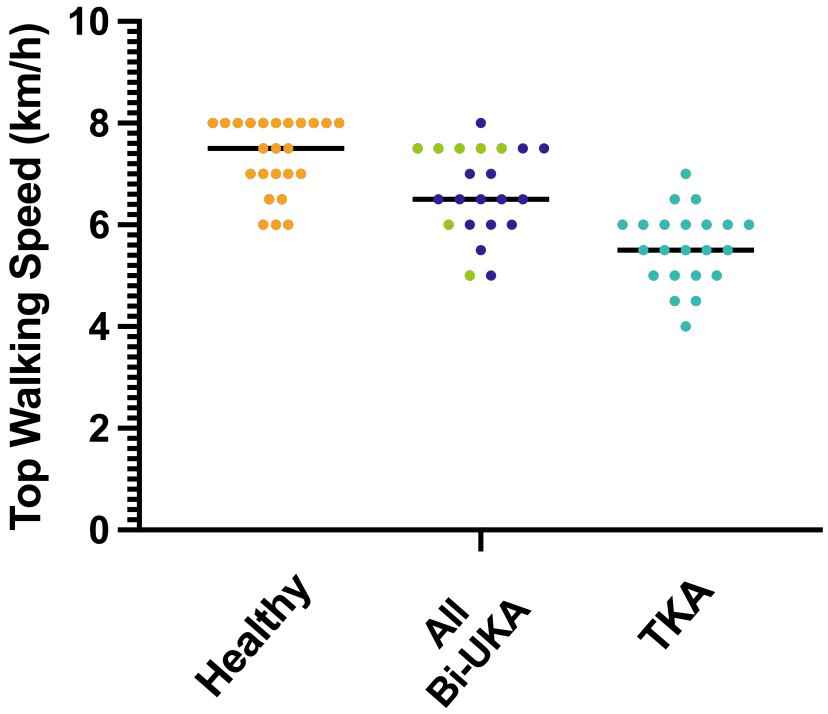


Figure 6.17. Median top walking speed (km/h) for subjects in study 4: Bi-Unicondylar Arthroplasty (Primary and Staged Bi-UKA) compared to healthy subjects and posterior-cruciate retaining total knee arthroplasty (TKA). Of the Bi-UKA group, the individual procedures are depicted: primary B-Bi-UKA (green), staged bi-unicondylar arthroplasty (dark purple).

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6.12.4 Vertical Ground Reaction Forces

At top walking speeds, both Bi-UKA and TKA groups had reduced maximum weight acceptance force compared to healthy subjects but also differed from each other, with Bi-UKA closer to the healthy range (Healthy vs Bi-UKA $p<0.02$, healthy vs TKA $p<0.001$, Bi-UKA vs TKA $p<0.02$, Table 6.9, Figure 6.18). Similarly, Bi-UKA and TKA had higher mid-stance forces compared to healthy subjects (Healthy vs Bi-UKA $p=0.003$, Healthy vs TKA $p<0.001$), but Bi-UKA was again closer to the healthy range (Table 6.9, Figure 6.18, Bi-UKA vs TKA $p<0.009$). Bi-UKA had nearer-normal cadence, contact, double support and gait cycle times a(all $p<0.01$, Table 6.9).

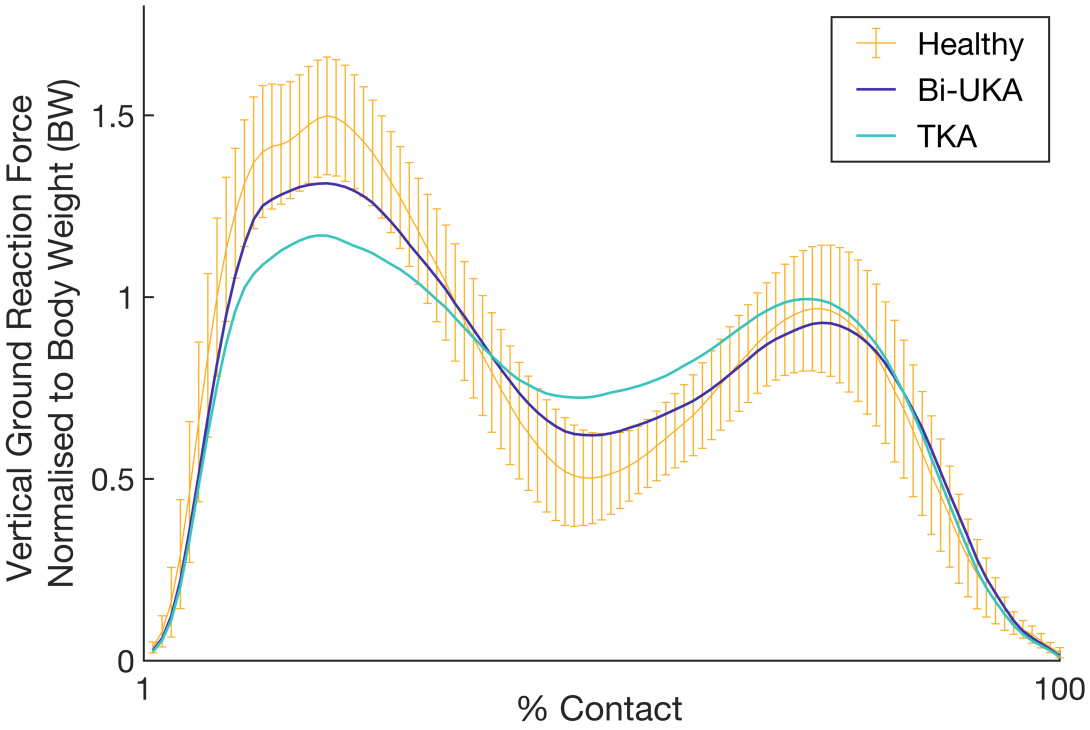


Figure 6.18. Vertical ground reaction forces during stance phase of gait for staged combined partial knee arthroplasty subjects (Staged CPKA) compared to primary posterior-cruciate retaining total knee arthroplasty (TKA), normal range for healthy subjects shown with 95% confidence intervals

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6.12.5 Step and Stride Lengths

Both arthroplasty groups had shorter step and stride lengths than healthy subjects. Bi-UKA measured mean 3cm (3%) shorter step lengths, though this did not reach significance (p=0.8). TKA were mean 12cm (13%) shorter in step length than healthy subjects (p=0.003). Bi-UKA had mean 9cm (12%) longer step lengths than TKA (p=0.003). Bi-UKA median step length were 80cm (IQR 76 – 85cm, Figure 6.25), while healthy controls measured median 84cm (IQR 79 – 92cm). TKA measured shorter step lengths, median 72cm (IQR 69 – 77cm). Differences in step length were replicated in stride length. Bi-UKA had a 7cm (4%) shorter mean stride length than healthy subjects (p=0.5) but 13cm (9%) longer than TKA (p=0.048, Table 6.9). TKA had the shortest stride lengths, 20cm (12%) shorter than healthy subjects (p=0.003). Bi-UKA median stride length were 159cm (IQR 152 – 170, Figure 6.19), 10cm shorter than healthy subjects, median 169cm (IQR 158 – 184cm), but 10cm longer than TKA, median 149cm (IQR 140 – 162cm). Primary Bi-UKA had longer step and stride lengths than staged Bi-UKA (Figure 6.19), though the number of primary Bi-UKA did not reach statistical power.

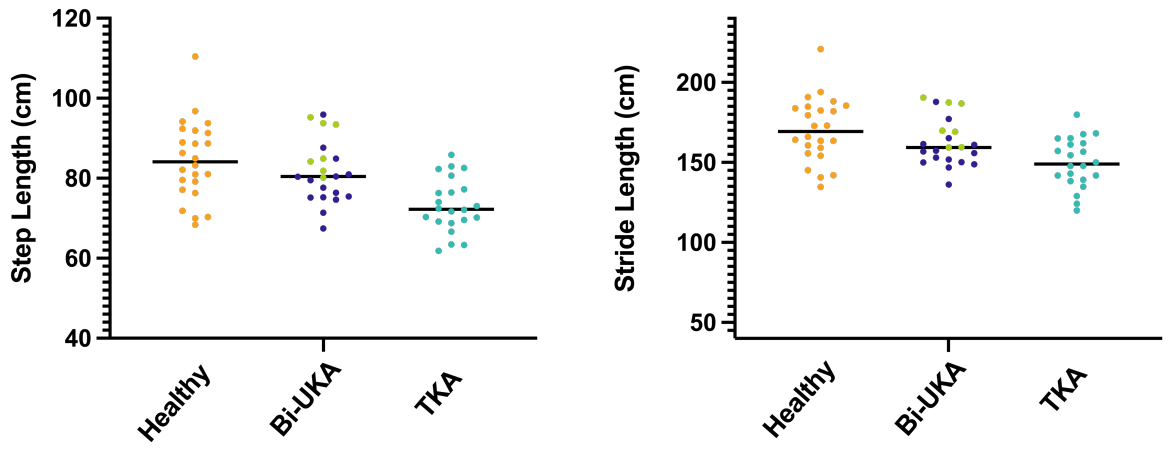


Figure 6.19. Median step length for all Bi-Unicondylar arthroplasty (Bi-UKA) subjects compared to matched healthy subjects (orange) and posterior-cruciate retaining total knee arthroplasty (blue) subjects (TKA). Bi-UKA group, the individual procedures are depicted: Primary Bi-UKA (green), staged Bi-UKA (dark purple)

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6.13 The Gait of Staged Bi-Unicondylar Arthroplasty

6.13.1 Publication

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Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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6.13.2 Patients

The staged Bi-UKA were the largest subgroup of the staged CPKA, and the only one to reach statistical power. Of the 15 staged Bi-UKA, eight subjects had undergone primary UKA-M with subsequent addition of UKA -L, while seven subjects underwent primary UKA-L with later addition of UKA-M. Twenty-eight potential staged Bi-UKA subjects were excluded, as detailed in Figure 6.6 and Table 6.1. The staged Bi-UKA cohort were re-matched with healthy (n = 20) and TKA (n = 19) controls. Specific to this and the 'all' Bi-UKA studies, TKA subjects with PFJ KL ≥ 2 OA were excluded regardless of other compartmental involvement (n = 5). The matched TKA subjects were performed for isolated medial OA (n = 12), isolated lateral OA (n = 4) and medial with lateral OA (n= 3, Figure 6.7) The Staged Bi-UKA were mean 22 ± 22 months post-conversion to Bi-UKA surgery at the time of the treadmill assessment, compared to 51 ± 52 for the TKA controls, though this did not reach statistical significance (p=0.6). The median months post-surgery were more evenly matched (Staged Bi-UKA 17, range 5-81, TKA 24 months, range 6-150 months, p=0.7, Table 6.10).

Subject	Healthy	Staged Bi-UKA	TKA	P value
Number of Knees (N =)	20	15	19	
Sex: M:F (% Male)	13 : 7	10 : 5	12 ± 7	1.0
Age (Years)	64 ± 8	71 ± 10	69 ± 10	0.1
Body Mass Index (kg/m²)	26.1 ± 3.8	28.2 ± 5.4	27.6 ± 3.7	0.3
Height (cm)	173 ± 11	172 ± 7	175 ± 11	0.7
Mean Months Post-Surgery		22 ± 22	51 ± 52	0.06
Median Months Post-Surgery (Range)		17 (5 – 81)	24 (6 – 150)	0.7

Table 6.10. Demographics of the groups included in study 5: staged bi-unicondylar arthroplasty (Staged Bi-UKA) subjects compared to healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA). All values are means with standard deviation unless otherwise specified. Sex and median months post-surgery are each compared with a Chi-Square test. All other demographics are compared with ANOVA.

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6.13.3 Top Walking Speeds

As with the previous studies, both staged Bi-UKA and primary TKA were slower than healthy controls (Table 6.11) Staged Bi-UKA were 11% slower ($p<0.02$) while TKA were 24% slower ($p<0.001$). Staged Bi-UKA were 18% faster than TKA ($p<0.006$). The differences in top walking speed remained the case after correcting for leg length (all Hof Speed $p<0.03$).

Subject	Healthy	Staged Bi-UKA	TKA
Top Walking Speed (km/h)	7.3 ± 0.7	6.5 ± 0.8 [a,b]	5.6 ± 0.8 [a,b]
Hof Speed (H)	0.74 ± 0.1	0.66 ± 0.1 [a,b]	0.56 ± 0.1 [a,b]
Weight Acceptance Rate (BW/s)	10.8 ± 3.7	10.5 ± 3.8 [b]	7.4 ± 3.8 [a,b]
Maximum Weight Acceptance Force (BW)	1.6 ± 0.2	1.4 ± 0.1 [b]	1.3 ± 0.2 [a,b]
Mid-Stance Force (BW)	0.47 ± 0.1	0.61 ± 0.1 [a,b]	0.69 ± 0.1 [a,b]
Push-Off Force (BW)	1.0 ± 0.1	0.95 ± 0.1	1.0 ± 0.1
Push-Off Rate (BW/s)	4.2 ± 0.8	4.0 ± 0.9	3.7 ± 0.9
Step Length (cm)	84 ± 10	79 ± 7	73 ± 7 [a]
Stride Length (cm)	179 ± 20	157 ± 13	151 ± 16 [a]
Step Width (cm)	13 ± 3	14 ± 2	13 ± 3
Cadence (Step/min)	59.8 ± 5.3	58.2 ± 5.8 [b]	52.3 ± 4.8 [a,b]
Impulse (BW/s)	382 ± 21	380 ± 21	376 ± 28
Double Support Time (s)	0.28 ± 0.1	0.28 ± 0.1 [b]	0.36 ± 0.1 [a,b]
Gait Cycle Time (s)	2.0 ± 0.2	2.1 ± 0.2 [b]	2.3 ± 0.2 [a,b]
Contact Time (s)	1.3 ± 0.1	1.3 ± 0.1 [b]	1.5 ± 0.1 [a,b]

Table 6.11. Gait characteristics at top walking speeds. Indicated values are means ± standard deviation. BW = normalised to body weight. All variables subject to Kruskal-Wallis then Mann-Whitney U with Bonferroni Correction. Significant differences ($p<0.05$) between groups annotated with superscript: [a] implant group compared to healthy control, [b] implant groups compared to each other. Where no superscript is noted, $p>0.05$.

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Median staged Bi-UKA TWS were 6.5km/h (IQR 6-7km/h), 1km/h slower than healthy subjects (median TWS 7.5km/h IQR 7-8km/h), median 1km/h faster than TKA (median TWS 5.5km/h, IQR 5 – 6km/h).

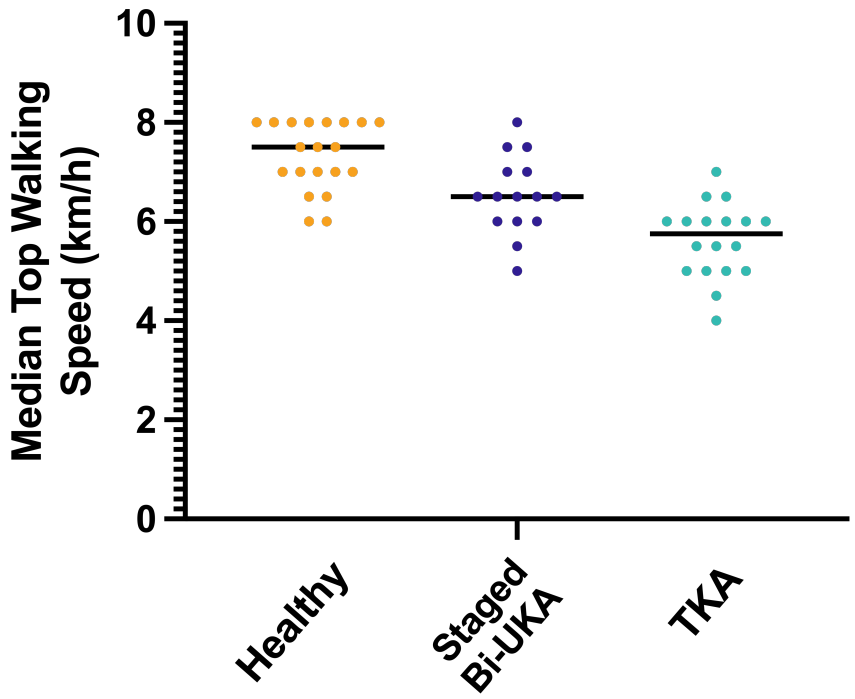


Figure 6.20. Median top walking speed (km/h) for subjects in study 5: staged bi-unicondylar knee arthroplasty (Staged Bi-UKA) compared to healthy subjects and posterior-cruciate retaining total knee arthroplasty (TKA).

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6.13.4 Vertical Ground Reaction Forces

Staged Bi-UKA demonstrated near-normal weight acceptance rate (Bi-UKA Vs Healthy p= 1) whilst for TKA it was reduced (TKA Vs healthy p=0.02. TKA Vs Staged Bi-UKA p=0.03, Table 6.11, Figure 6.21). Staged Bi-UKA measured a reduced maximum weight acceptance force, but this did not reach significance compared to healthy subjects (p=0.13), whereas TKA was reduced against healthy controls (p<0.001) and staged Bi-UKA (p=0.02). Both arthroplasty groups recorded mid-stance forces higher than the normal range, with TKA the highest (staged Bi-UKA Vs Healthy p= 0.003, TKA Vs Healthy p<0.001, staged Bi-UKA Vs TKA p=0.048). The differences between the groups at push-off were small and did not reach significance (all p>0.9).

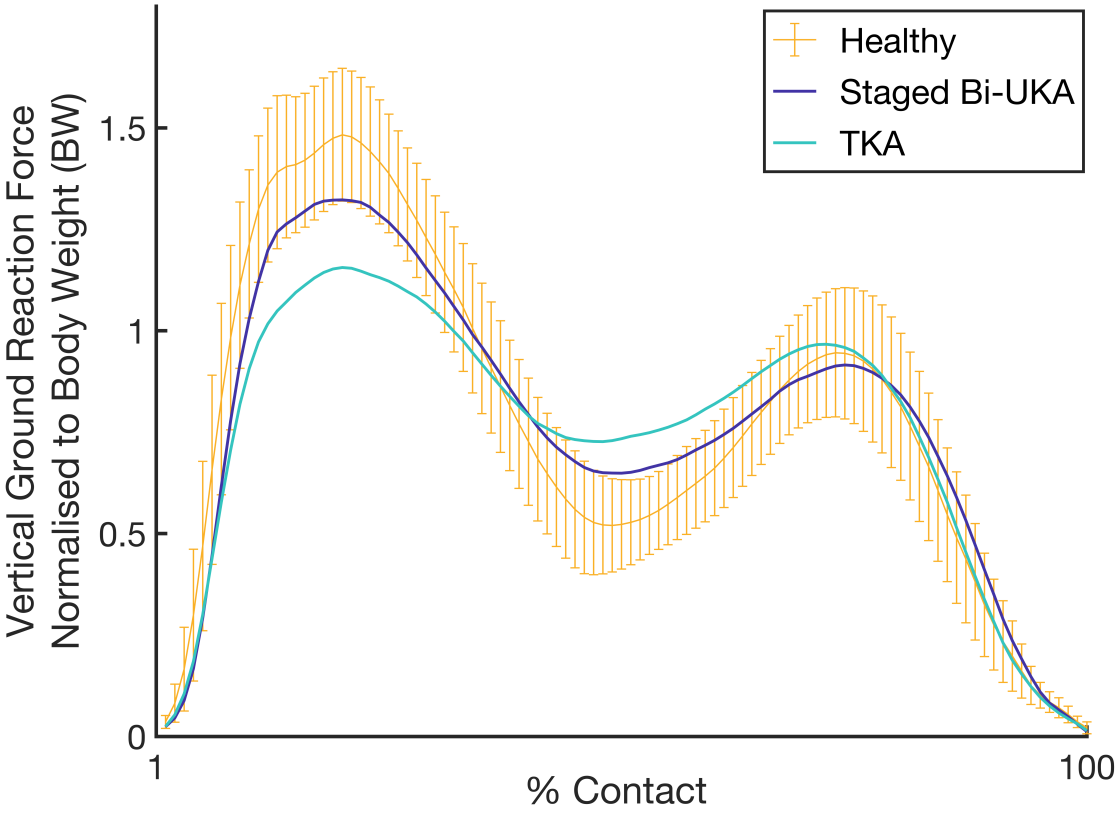


Figure 6.21. Vertical ground reaction forces during stance phase of gait for staged bi-unicondylar arthroplasty subjects compared to primary posterior-cruciate retaining total knee arthroplasty (TKA), normal range for healthy subjects shown with 95% confidence intervals.

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Staged Bi-UKA recorded a near-normal cadence (Vs healthy p=1), while TKA had a lower cadence compared to healthy controls (p<0.001, Table 6.11) and staged Bi-UKA (p<0.02). Staged Bi-UKA had near normal double-support, gait cycle and contact times (Vs healthy, all p=1) whereas TKA recoded longer times compared to healthy controls (all p<0.003) and staged Bi-UKA (p<0.02, Table 6.11).

6.13.5 Step and Stride Lengths

Staged Bi-UKA and TKA both recorded shortened step and stride lengths (Table 6.11). Compared to the healthy subjects' mean step lengths of 84 ± 10cm, staged Bi-UKA were 5cm (6%) shorter (mean 79 ± 7cm , p=0.2). TKA recorded the shortest step lengths (mean 73 ± 7cm), 11cm (13%) shorter than healthy subjects (p=0.003). Staged Bi-UKA had mean 6cm (8%) longer step lengths than TKA, which did not reach significance (p=0.1). Staged Bi-UKA median step length were 78cm (IQR 75 – 81), 5cm shorter than healthy subjects (median 83cm, IQR 79 – 89) and 6cm longer than TKA (median 72cm, IQR 69 – 77cm, Figure 6.22).

Mean stride length of staged Bi-UKA were 157 ± 13cm, 13cm (7%) shorter than healthy controls (170 ± 20cm, p=0.1), and 6cm (5%) longer than TKA (mean 151 ± 16cm), though this did not reach significance, p=0.8). TKA recorded 19cm (11%) shorter strides on average than healthy controls (p=0.009). Median stride length of staged Bi-UKA were 156cm (IQR 150 – 161cm), 9cm shorter than healthy subjects (165cm, IQR 148 – 183cm), 6cm longer than primary TKA (150cm, IQR 141 – 162cm, Figure 6.22).

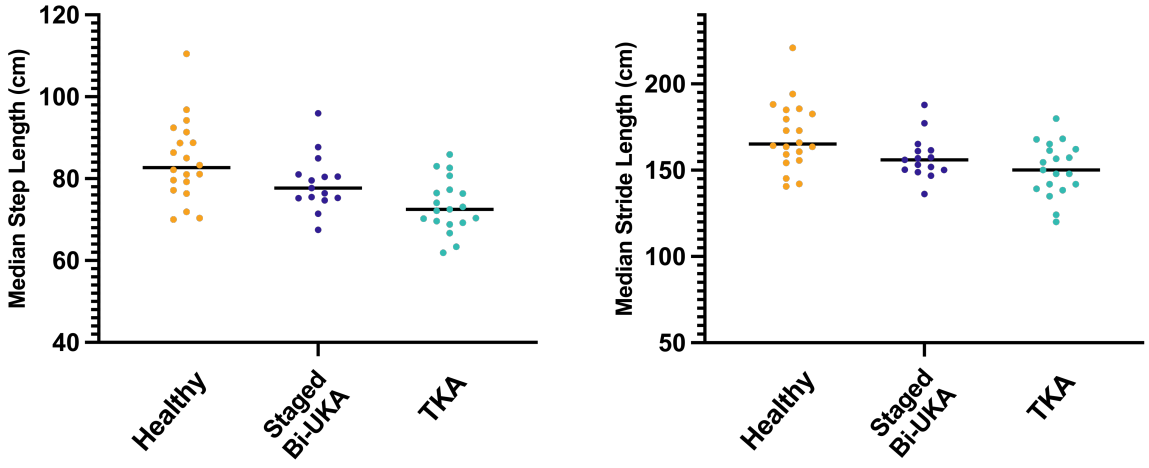


Figure 6.22. Median step length for staged bi-unicondylar arthroplasty (Staged Bi-UKA) subjects compared to matched healthy subjects and posterior-cruciate retaining total knee arthroplasty subjects (TKA).

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6.14 The Gait of Staged Combined Partial Knee Arthroplasty

6.14.1 Publication

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Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. The compartmental approach to revision of partial knee arthroplasty results in nearer-normal gait and improved patient reported outcomes compared to total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2021 Aug 20. doi: 10.1007/s00167-021-06691-9.

6.14.2 Patients

In study 6, all staged CPKA procedures were analysed collectively. Of the 74 subjects considered for the study, 23 were included (Figure 6.6) whilst 51 were excluded (Table 6.1). The staged CPKA cohort included BCA-M (N = 5, 83% female), BCA-L (N = 3, 100% female) and Bi-UKA (N = 15, 27% female). Of this group, eight subjects had undergone primary PKA under the care of other surgeons, therefore, the combinations of implants varied (Table 13.1). Five of the staged CPKA group had undergone contralateral UKA-M and one had a contralateral UKA-L. Twenty-two sex, BMI and age-appropriate healthy controls were matched to the CPKA group. Similarly, 23 posterior cruciate-retaining TKA subjects entered this study, of whom 15 had single compartment KL ≥ 2 OA pre-TKA (medial n = 12, lateral n = 3). The remaining 8 subjects had two-compartment disease (medial and lateral n = 5, medial and patellofemoral n = 3, Figure 6.7). TKA subjects were mean 20months further from surgery than the staged CPKA group, though this did not reach significance (p=0.08, Figure 6.23). Median CPKA time from surgery to gait assessment were 17 months (range 4-81 month), compared to the TKA group, whom were 16 months post-surgery (range 6-150 months, p=0.6, Table 6.12

Subject	Healthy	Staged CPKA	TKA	P value
Number of Knees (N =)	22	23	23	
Sex: M:F (% Male)	10 : 12 (45%)	11 : 12 (48%)	10 : 13 (43%)	1.0
Age (Years)	64 ± 8	68 ± 10	68 ± 10	0.2
Body Mass Index (kg/m^2)	26.8 ± 5.4	28.4 ± 5.4	28.7 ± 3.5	0.4
Height (cm)	170 ± 9	172 ± 6	171 ± 11	0.8
Mean Months Post-Surgery		22 ± 21	42 ± 50	0.08
Median Months Post-Surgery (Range)		17 (4 – 81)	16 (6 – 150)	0.6

Table 6.12. Demographics of the groups included in study 4: staged combined partial knee arthroplasty (staged CPKA) subjects compared to healthy controls and posterior-cruciate retaining total knee arthroplasty (TKA). All values are means with standard deviation unless otherwise specified. Sex and median months post-surgery are each compared with a Chi-Square test. All other demographics are compared with ANOVA.

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6.14.3 Top Walking Speeds

The staged CPKA group walked, on average, 16% faster than primary TKA, though neither arthroplasty group walked as fast as the healthy subjects ($p<0.01$, Table 6.13). Staged CPKA were 12% slower than healthy controls, while TKA were 25% slower ($p<0.001$). In all instances, this remained the case after correcting for leg length (Hof $p<0.003$).

Subject	Healthy Controls	Staged CPKA	TKA
Top Walking Speed (km/h)	7.2 ± 0.7	6.4 ± 0.8 [a, b]	5.5 ± 0.7 [a, b]
Hof Speed (H)	0.73 ± 0.1	0.64 ± 0.1 [a, b]	0.55 ± 0.1 [a, b]
Weight Acceptance Rate (BW/s)	10.8 ± 3.5	10.6 ± 3.6 [b]	6.8 ± 2.6 [a, b]
Maximum Weight Acceptance Force (BW)	1.6 ± 0.2	1.4 ± 0.2 [a, b]	1.2 ± 0.1 [a, b]
Mid-Stance Force (BW)	0.5 ± 0.1	0.6 ± 0.1 [a, b]	0.7 ± 0.1 [a, b]
Push-Off Force (BW)	0.98 ± 0.2	0.96 ± 0.1	0.97 ± 0.1
Push-Off Rate (BW/s)	4.1 ± 1.0	4.0 ± 0.9	3.6 ± 0.7
Step Length (cm)	82 ± 8	79 ± 7 [b]	70 ± 7 [a, b]
Stride Length (cm)	165 ± 16	156 ± 14	144 ± 17 [a]
Step Width (cm)	12 ± 3	14 ± 2	13 ± 4
Cadence (Step/min)	60.0 ± 5.2	56.8 ± 5.4	53.1 ± 5.2 [a]
Impulse (BW/s)	387 ± 23	378 ± 22	375 ± 21
Double Support Time (s)	0.28 ± 0.1	0.29 ± 0.1 [b]	0.36 ± 0.1 [a, b]
Gait Cycle Time (s)	2.0 ± 0.2	2.1 ± 0.2	2.3 ± 0.2 [a]
Contact Time (s)	1.3 ± 0.1	1.4 ± 0.1 [b]	1.5 ± 0.2 [a, b]

Table 6.13. Gait characteristics at top walking speeds. Indicated values are means ± standard deviation. BW = normalized to body weight. All variables subject to Kruskal-Wallis then Mann-Whitney U with Bonferroni Correction. Significant differences ($p<0.05$) between groups annotated with superscript: [a] implant group compared to healthy control, [b] implant groups compared to each other. Where no superscript is noted, $p>0.05$.

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Staged CPKA median TWS were 6.5 km/h (IQR 5.8 – 7 km/h), 0.75 km/h slower than healthy subjects (median TWS 7.25 km/h, IQR 6.6 – 8 km/h) but 1 km/h faster than TKA (median TWS 5.5km/h, IQR 5 – 6 km/h, Figure 6.17).

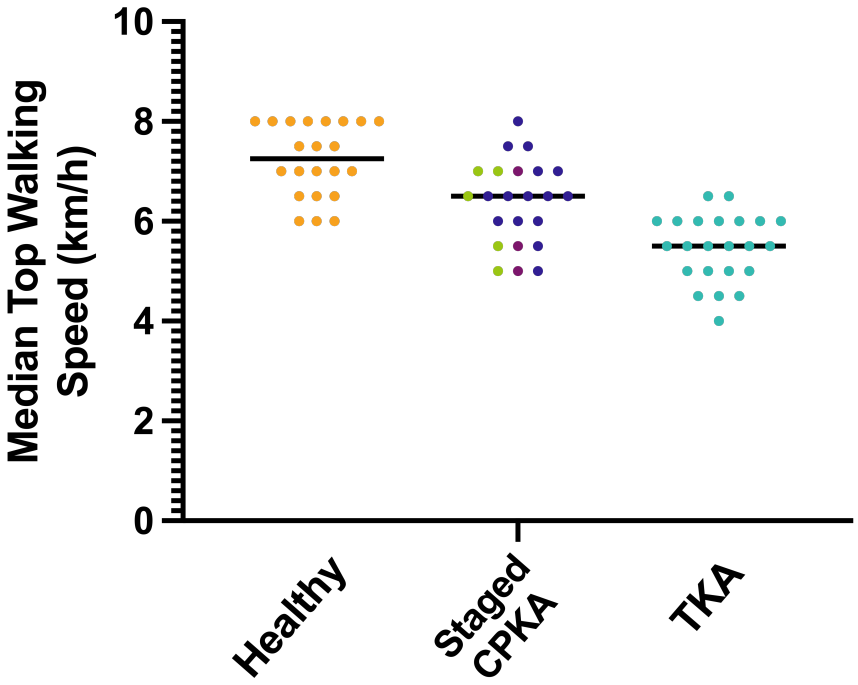


Figure 6.23. Median top walking speed (km/h) for subjects in study 4: staged combined partial knee arthroplasty (Staged CPKA) compared to healthy subjects and posterior-cruciate retaining total knee arthroplasty (TKA). Of the Staged CPKA group, the individual procedures are depicted: staged medial bicompartmental arthroplasty (green), staged lateral bicompartmental arthroplasty (light purple), staged bi-unicondylar arthroplasty (dark purple).

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6.14.4 Vertical Ground Reaction Forces

At top walking speeds, CPKA had near-normal weight-acceptance rate (CPKA vs healthy p=1, Table 6.13) whereas TKA weight-acceptance was reduced compared to healthy (p<0.001) and CPKA (p<0.006) subjects (Figure 6.24). Both implant groups demonstrated reduced maximum weight acceptance force compared to the healthy subjects, though TKA was associated with a greater reduction (healthy vs CPKA p=0.006, healthy vs TKA p<0.001, CPKA vs TKA p=0.009, Table 6.13, Figure 6.24). Similarly, CPKA and TKA demonstrated higher mid-stance forces than healthy subjects (p<0.001), but the difference was smaller following CPKA (CPKA vs TKA p<0.03). All groups showed similar push-off force (p>0.2, Figure 6.24). CPKA had nearer normal contact time (CPKA vs TKA p=0.012) and double support time (CPKA vs TKA p<0.01).

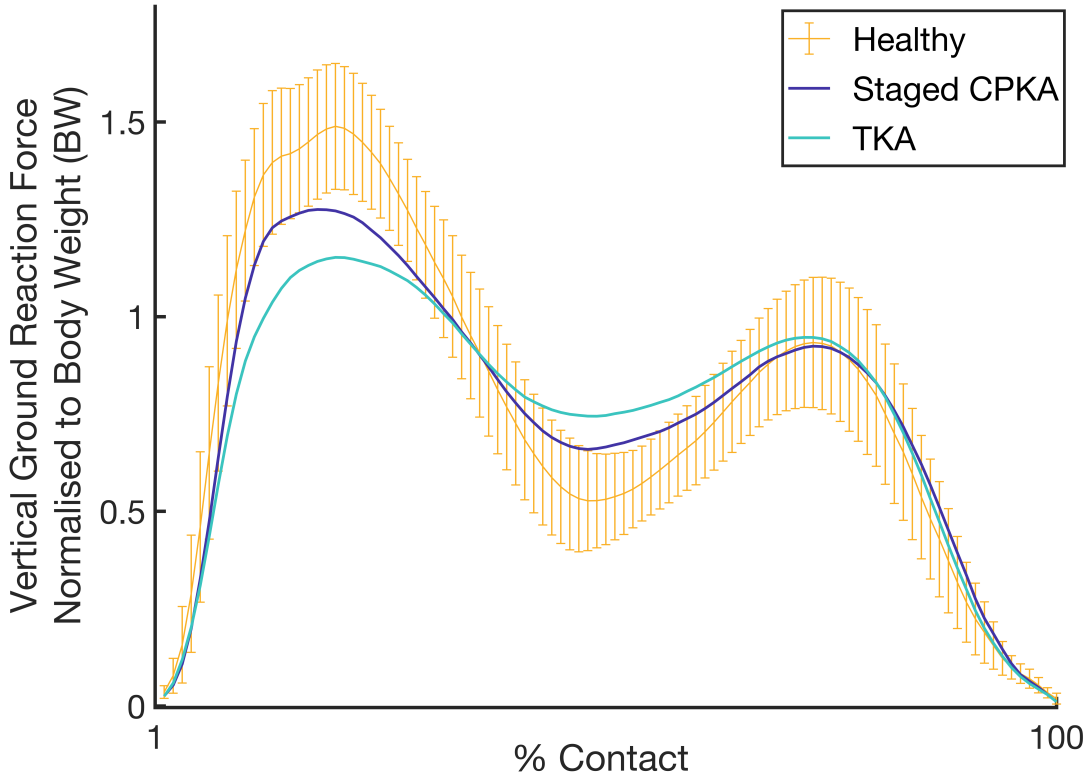


Figure 6.24. Vertical ground reaction forces during stance phase of gait for staged combined partial knee arthroplasty subjects (Staged CPKA) compared to primary posterior-cruciate retaining total knee arthroplasty (TKA), normal range for healthy subjects shown with 95% confidence intervals.[442]

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6.14.5 Step and Stride Lengths

Both arthroplasty groups had shorter step and stride lengths than healthy subjects. Staged CPKA measured mean 3cm (4%) shorter step lengths, though this did not reach significance (p=0.2). TKA were mean 12cm (14%) shorter in step length than healthy subjects (p<0.001). Staged CPKA had mean 9cm (11%) longer step lengths than TKA (p<0.003) Differences in step length were replicated in stride length. Staged CPKA had a 9cm (5%) shorter mean stride length than healthy subjects (p=0.2) but 12cm (9%) longer than TKA, which approached but did not reach significance (p=0.051). TKA had the shortest stride lengths, 21cm (13%) shorter than healthy subjects (p<0.001, Table 6.13).

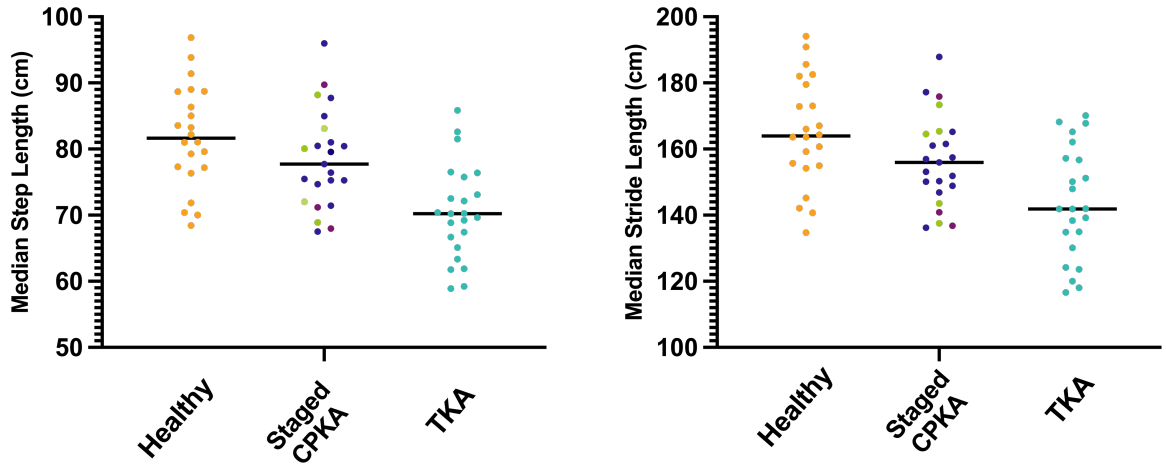


Figure 6.25. Median step length for all staged combined partial Knee arthroplasty (Staged CPKA) subjects compared to matched healthy subjects and posterior-cruciate retaining total knee arthroplasty subjects (TKA). Staged CPKA group, the individual procedures are depicted: staged medial bicompartmental arthroplasty (green), staged lateral bicompartmental arthroplasty (light purple), staged bi-unicondylar arthroplasty (dark purple)

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Staged CPKA median step length were 78cm (IQR 73 – 82cm, Figure 6.25), while healthy controls measured median 82cm (IQR 77 – 88cm). TKA measured shorter step lengths, median 70cm (IQR 66 – 74cm). Staged CPKA median stride length were 156cm (IQR 148 – 165, Figure 6.25), 8cm shorter than healthy subjects, median 164cm (IQR 155 – 178cm), but 12cm longer than TKA, median 142cm (IQR 133 – 157cm).

6.15 Discussion

Arthroplasty performance can be objectively assessed using gait analysis on the instrumented treadmill. A summary of differences found from each study is shown in Table 6.14. Failure to detect any differences between BCA-L and TKA may indicate that the implants have a similar performance in the gait lab, although failure to find any statistical differences whatsoever more likely suggest that study 3 were underpowered. In either case, the results will not be included in the discussion, however, the limitations are discussed at length toward the end of the chapter.

	All CPKA	Primary BCA-M	Primary BCA-L	Primary & Staged Bi-UKA	Staged Bi-UKA	Staged CPKA
Top Walking Speed (km/h)						
Hof Speed (H)						
Weight Acceptance Rate (BW/s)				0.06		
Maximum Weight Acceptance Force (BW)						
Mid-Stance Force (BW)						
Push-Off Force (BW)						
Push-Off Rate (BW/s)						
Step Length (cm)						
Stride Length (cm)						0.051
Step Width (cm)						
Cadence (Step/min)						
Impulse (BW/s)						
Double Support Time (s)						
Gait Cycle Time (s)						
Contact Time (s)						

Table 6.14 Summary of gait differences between compartmental arthroplasty and total knee arthroplasty subjects for each study. Cells shaded purple suggest a statistically significant (Mann-Whitney Test with Bonferroni Correction $p<0.05$) nearer-normal advantage of the compartmental group compared to matched TKA groups. Blank cells indicate differences did not reach statistical significance.

Previous studies have reported an advantage of UKA-M over TKA at top walking speeds [317, 418, 419] which the current study suggests is preserved following CPKA. The subgroup analysis indicates TWS is significantly higher for all groups (Table 6.14). The reported difference in top walking speed are meaningful, since life expectancy improves significantly with every 0.1m/s increase in top walking speed, [23]. It is possible they indicate improved post-operative health in the study group, relative to their matched TKA counterparts[317, 418, 419 438].

Staged Bi-UKA and the overall Staged CPKA groups had significantly more normal weight-acceptance, and all groups recorded nearer-normal maximum weight-acceptance and mid-stance forces, with no significant differences found between the CPKA subgroups and the healthy controls. All were statistically better than TKA in these metrics (Table 6.14). The reduced extensor efficiency of TKA at the low flexion angles associated with fast walking may, in part, explain these differences, since the quadriceps are active during weight acceptance and mid- stance (Chapter 5.7)[387].

All CPKA subgroups had longer, nearer-normal step lengths than TKA, with all but the staged CPKA group recording significantly longer stride lengths too (Table 6.14). Staged CPKA stride lengths approached significance over TKA (p=0.051). The paradoxical anterior-posterior translation, described in Chapter 5, in relation to TKA may limit mid-swing flexion, reducing stride length and walking speed for TKA, in part potentially explaining why length is preserved with CPKA[24].

There is some evidence that BCA-M results in higher function during strenuous activity [255], but no studies to date have compared BCA-M to healthy controls and TKA at top walking speeds. The retention of the lateral compartment and the cruciate ligament complex may play an important role in allowing patients with a BCA-M to retain near normal stride length and speed following surgery (Table 6.14). Previous studies have reported an advantage of UKA-M over TKA at top walking speeds[317, 418, 419] which the current study suggests is preserved following primary modular BCA-M, most notably in top walking speeds and stride length [418, 419]. The previous studies of gait (predominantly with the monolithic design) included fewer BCA-M subjects walking at slower walking speeds to those investigated here (Chapter 3.3)[259, 268].

The Bi-UKA studies support the findings of Banks et. al[25], regarding the gait and kinematics of four Bi-UKA subjects and one subject with a TKA femoral component but medial and lateral tibial unicompartmental components, compared to contralateral healthy knees, UKA and TKA. Bi-UKA patients demonstrated higher knee flexion from heel-strike to mid-stance than TKA patients, but similar flexion in late stance through swing phase[312]. In the current study, Bi-UKA demonstrate nearer normal vertical ground reaction forces in early stance, and equal those of TKA at push-off and the combined primary and staged group measured nearer-normal step and stride lengths, longer than matched TKA.

The staged CPKA patients more closely resemble UKA patients and healthy controls from earlier publications[418, 419], both in speed and other characteristics of gait, notably stride length. This study

indicates that despite second surgery, patients converted to CPKA, for native compartment osteoarthritis, were found to have a more normal gait than matched high functioning primary TKA subjects, in whom, surgery had been performed for one or two compartment disease with the reverse trend not identified for any of the measured metrics.

6.16 Limitations of the gait study

The gait studies in this thesis have significant limitations. First, gait is a complex and multifactorial action, yet this study has simplified it to just the vertical component of ground reaction force and basic temporospatial measurements. The reason for this was logistical, a number of patients had been measured prior to the commencement of this PhD, without the simultaneous recording of motion capture data. The decision was made not to re-measure these patients, so in order to include them in the study, motion capture analysis was excluded. Similarly, electromyography, live fluoroscopy and functional activities including sit-to-stand, stair ascent and descent, slope walking and squatting exercises give a more complete picture of clinical function and would have enhanced this study significantly.

The study focused on TWS, in order to test the implants to the limits of their capabilities. It is difficult to discern whether patients actually walk at these speeds in their everyday lives. Fast walking overlooks function at self-selected slower walking speeds, and prevents direct comparisons of patients at like-for-like speeds. The rationale for this is that if all subjects are compared at the same speed, some will be at the limits of maximum performance, whilst others will be walking with relative ease, which substitutes one limitation for another.

The numbers of CPKA patients in each study were small, and patients were not randomised, nor were they propensity matched. Subjects were drawn from Professor Cobb's patient group, which, in general, is a specialist referral practice with many patients specifically seeking treatment in relation to Professor Cobb's expert skills in partial knee surgery. It is possible, therefore, that the population of CPKA subjects used in this study was not truly representative of the normal population of patients seen in routine clinical practice. This may have a bearing on the appropriateness of comparison to the selected TKA subjects, the majority of whom were drawn from a standard practice.

TKA subjects were drawn retrospectively from a prospectively collected database, meaning that the timing of measurement on the instrumented treadmill varied quite significantly, with some subjects

measured relatively early in their recovery phase, whilst others had undergone surgery much longer ago. The TKA group were further from surgery, meaning they likely had had more opportunity to recover and rehabilitate[216, 443]. If so, the effect would favour the TKA group, meaning that false positives are less likely, strengthening the conclusions of this work.

This study would have benefited from pre-operative data to determine the extent of improvement each subject experienced as a consequence of surgery. This was reflective of the retrospective nature of data collection. However, attempts were made to mitigate its absence by only selecting TKA patients who underwent surgery for single or two-compartment disease, and those who did not have pre-operative evidence of ACL dysfunction. All would have been eligible for PKA or CPKA under the senior author's current clinical practice. The inclusion of patients with single compartmental disease in the TKA group was necessary to power each study but may have acted to the detriment of the compartmental arthroplasty group, whom all had two-compartment disease pre-operatively.

Whilst we endeavoured to include all subjects, the number of exclusions from this study is high, indicating there is likely a selection bias and important data will be missing. Specifically, 12 patients (6% of eligible participants) could not be contacted, whilst 10 patients (5%) were invited but declined. Reasons for unwillingness to participate were predominantly logistical, Professor Cobb has a specialist referral practice with patients from all over the world, so attending the gait lab for assessment was not feasible for a number of these patients. No cases of significant discontent were noted among the patients who declined.

For study 1 (all CPKA) and study 6 (all staged CPKA), the route to CPKA was variable. The heterogeneity of the groups in terms of procedure order and type, primary and secondary surgery, implant type and time to second surgery for the staged procedures is a limitation of the study. Similarly, the study is underpowered for specific implant brands or revision rates. A much larger study would be required to indicate whether some subtypes demonstrate advantages over others.

The specific limitations of study 3, primary BCA-L, include the significant difference in time between surgery and gait measurement ($p=0.03$). Unlike the other CPKA studies, the small BCA-L cohort were predominantly female, and three subjects had simultaneous bilateral procedures. This inevitably meant that the function of one knee impacted on that of the other, so if one knee demonstrated poor performance, the second knee would likely be affected. With such a small sample size, this may lead to significant errors. The power calculation anticipated that the CPKA, in this case BCA-L, may

be up to 15% faster. Here, BCA-L were statistically similar to TKA, which indicates that the implants may have the same performance, but it is equally possible that the study were underpowered.

Finally, all CPKA procedures were performed by an expert high-volume partial knee arthroplasty surgeon. There is evidence that surgeons with a higher proportion of PKA practice have better outcomes[293, 444], therefore the results may not be generalisable to low-volume PKA surgeons at this juncture. This may be addressed in the future through additional training for arthroplasty surgeons.

6.17 Chapter Summary

This chapter has sought to understand the gait of compartmental arthroplasty and how it compares to that of healthy subjects and those treated with the current gold-standard, posterior-cruciate retaining TKA. Through the measurement of ground reaction forces and temporospatial metrics, there looks to be a significant functional advantage of bone, cruciate and peri-articular preserving compartmental arthroplasty. Faster speeds, longer strides and more normal forces in early stance indicate that CPKA, both as a primary and staged procedure has the potential to deliver high-performance and nearer-native kinematics in the treatment of multi-compartment arthrosis.

7 Patient Reported Outcomes

Publications

This chapter includes text and images from the following publications, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. Medial bicompartmental arthroplasty patients display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients. Knee Surg Sports Traumatol Arthrosc. 2021 Oct 23. doi: 10.1007/s00167-021-06773-8

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Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. The compartmental approach to revision of partial knee arthroplasty results in nearer-normal gait and improved patient reported outcomes compared to total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2021 Aug 20. doi: 10.1007/s00167-021-06691-9.

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Contributions

The majority of the work in this chapter was independent, however, during the project approximately 40% of patients were recruited to JointPRO by others, including Miss Emily Moore (Research Assistant), Ms Brogan Guest (Physician Associate) and Ms Maria Woringer (Research Assistant). The remaining 60% were recruited by Amy Garner. All data gathering, processing and analysis were performed independently by Amy Garner.

7.1 Motivation

The ultimate success or failure of a procedure rests with the patient's lived experience of it. The dissatisfaction rates of up to 25% associated with TKA are well-described and do not appear to be reducing. The subjective outcomes of CPKA in either the primary or staged setting are relatively unknown. This chapter seeks to understand whether there may be a difference in post-operative outcomes of CPKA, worthy of further study.

7.2 Abstract

7.2.1 Aims of the study

This study looks to compare the Oxford Knee Score and Euro-Qol 5D following CPKA and subgroups of compartmental arthroplasty to those of demographically matched subjects following posterior-cruciate retaining TKA.

7.2.2 Patients and Methods

At the time of gait assessment (Chapter 6), participants were asked to complete Oxford Knee Scores (OKS) and EuroQol-5D 5 Level (EQ-5D) scores. Scores were analysed by CPKA procedure group and compared with the Mann-Whitney test, to demographically matched posterior-cruciate retaining TKA participants. Responses were further analysed by overall score, and by individual question or domain and according to the minimal clinically important difference (MCID) of 5 points on the OKS.

7.2.3 Results

All CPKA groups recorded statistically significant ($p<0.05$) higher OKS and EQ-5D scores compared to TKA, with mean OKS scores exceeding the MCID in the Primary BCA-M, the primary and staged Bi-UKA and the staged Bi-UKA groups. Median scores exceeded the MCID. All groups exceeded the MCID for mean and median EQ-5D scores. Trajectories indicated that these differences are maintained out to 7 years following surgery.

7.2.4 Discussion

The data presented in this study are a 'snap shot' of patient reported outcomes following CPKA. They suggest that following CPKA, in both the primary and staged settings, post-operative satisfaction and quality of life are high and exceed the scores of their matched TKA counterparts. Specific advantages were seen in quadriceps active actions including use of transport, sit to stand, kneeling, stair descent and instability symptoms.

7.2.5 Limitations

The study is underpowered for formal PROMs analysis. It analyses a single post-operative score per subject, with no account of pre-operative data, nor the change in scores over time. Whilst some statistically significant differences are reported, these did not always reach the previously defined Minimal Clinically Important Difference, so conclusions regarding the clinical impact of these results are difficult to draw. These important limitations are acknowledged from the outset and discussed in more detail towards the end of the chapter.

7.2.6 Conclusion

Following CPKA, in both the primary and staged settings, patients report high levels of satisfaction and good quality of life. There may be an advantage in patient reported outcomes of CPKA over TKA, worthy of further investigation, through an adequately powered study.

7.3 Introduction

Improved function, relief of pain and enhanced quality of life are the subjective hallmarks of satisfactory surgery[445]. Patient Reported Outcome Measures (PROMs) are in widespread use across the world.

7.3.1 Power Calculations

The power calculation of the TOPKAT study resolved that a sample size of 500 patients would be required to detect differences of 2 points on the OKS between UKA-M and TKA, with 80% power and 95% confidence[234]. The largest group studied in this thesis comes from study 1, CPKA (n= 60) Vs TKA

(n=28) and therefore this study is underpowered for detailed analysis and comparison of PROMs. Nonetheless, the results are presented here, in pilot form, to indicate whether there may be differences worthy of further formal study.

7.3.2 Timing of Data Collection

Participants in the gait analysis study were asked to complete the OKS and EQ-5D 5L at the time of their treadmill assessment. Invitations were sent two weeks prior to the gait lab appointment, and results were accepted for all responses collected up to one month following treadmill assessment.

7.3.3 Methods of Data collection

PROMs scores were collected in three ways:

1. Paper Based Surveys
2. Online surveys via www.jointpro.co.uk
3. Telephone-assisted Completion of Missing Tests

7.3.3.1 Paper Based Surveys

Prior to 2014, all subjects walking on the instrumented treadmill were asked to complete paper-based Oxford Knee Scores and the EQ-5D at the time of treadmill assessment (Appendix Figure 13.6). Between 2014 and 2018, a hybrid model of data collection was used, with the majority of patients completing online surveys (JointPRO.co.uk) while those who reported difficulties with JointPRO, continued to complete paper-surveys on validated forms. These paper copies remain on file in the MSk Laboratory archives (stored with ethical approval in a locked filing cabinet, within a locked office, with restricted access). Paper records were accessed in October and November 2019, to seek retrospective data collected on survey participants whom participated in the treadmill study. Scores were semi-anonymised (treadmill ID only) then uploaded to SPSS V27. for analysis.

7.3.3.2 Online surveys via www.jointpro.co.uk

Since its commission in 2014, all patients passing through the gait lab have been asked to register an account with www.jointpro.co.uk, a web-based survey tool designed and run by Imperial College

London, in partnership with the University of Oxford and patient.co.uk. Patients create an online account and input information regarding joint problems, operation dates and details, from drop down lists of options. When patients schedule a gait analysis appointment, they are sent an email, asking them to complete an Oxford Knee Score and EQ-5D using www.JointPro.co.uk portal. Participants answer the validated OKS questions (Appendix Figure 13.7) and score themselves 1-5 for EQ-5D (Appendix Figure 13.8). JointPRO has the capability to log scores for each hip and knee individually. Survey respondents are able to log as many scores as they wish, at any time point pre- or post-surgery, but once an operation date has been logged, the system automatically emails the patient six weeks post-surgery, then six months, one year and every year thereafter to prompt them to update their scores. Upon completion of the survey, the patient is shown a graphical representation of their data for that and any previous tests, so they may review their progress over time (Figure 7.1). This data is also accessible to the research team. Hovering over each point on the graph results in a full breakdown of each score by question.

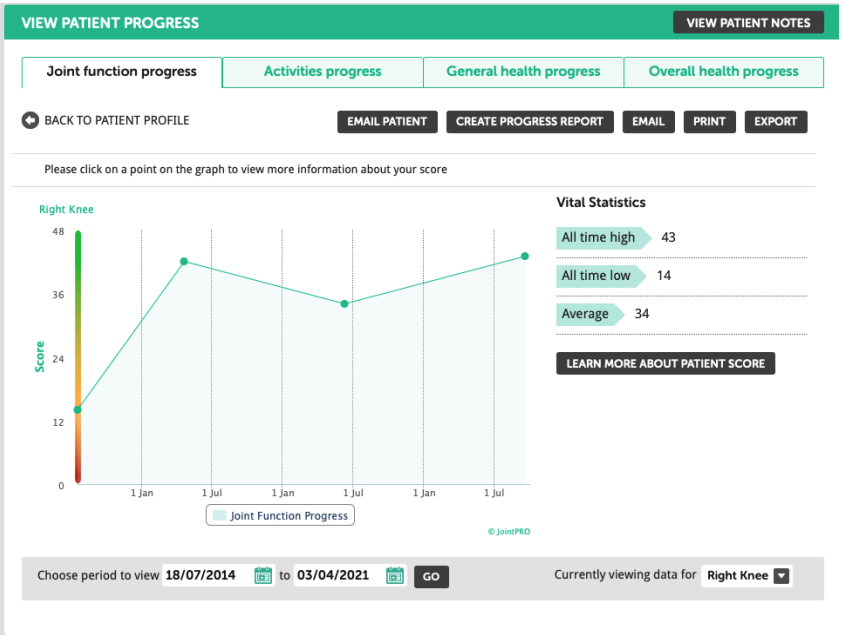


Figure 7.1. Graphical Representation of a subject's Oxford Knee Score over time, completed via JointPRO

Trends in scores may be traced over time, with changes in the clinical situation graphically displayed to demonstrate a significant event has occurred. For example, the patient to whom Figure 7.2 relates experienced a bearing dislocation after a fall but did not immediately present to hospital, recording a significant sudden dip in scores, which prompted clinical review and subsequent revision surgery.

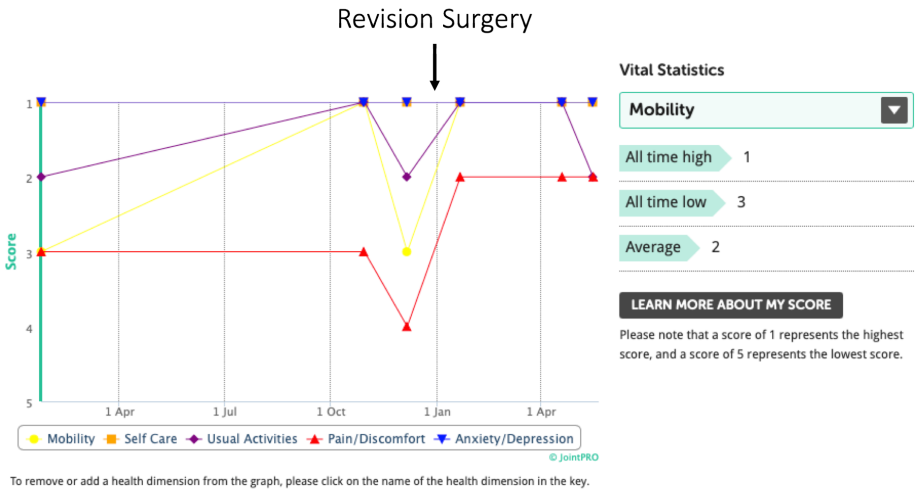


Figure 7.2. Graphical representation of a subject's Euro-Qol 5D Score over time, completed via JointPRO Each coloured line represents one of the five domains. The arrow depicts a time point on the graph where a revision procedure occurred after an acute event (mobile bearing dislocation).

Since 2019, a research assistant has cross-checked patient information against operating lists, clinical notes and radiographs to ensure that scores are logged against operative procedures. However, prior to 2019, the system relied on the operative information provided by the patient. For the study, all participants included in the CPKA groups and TKA controls were reviewed individually in JointPRO, their data retrieved and their operative data cross-checked with radiographs. Most common errors were found amongst the primary CPKA subjects, where often only one of the two PKA procedures had been recorded. Data were corrected prior to analysis. The system has since been modified to prevent this issue going forward.

Looking at each subject individually, some subjects had recorded multiple data at different time points pre- and post-op, whilst others had only recorded one score around the time of the treadmill assessment (within a window of 2 weeks prior to 4 weeks after). To make comparisons more direct, the score closest to the day of the treadmill assessment was taken. In the majority of cases, this was within two-weeks of the treadmill test.

7.3.3.3 Telephone-assisted Completion of Missing Tests

Between 25th November 2019 and 2nd December 2019, four subjects were measured on the instrumented treadmill, but did not complete JointPRO. A root cause analysis revealed two problems had occurred, the first was that the website was undergoing transition from one server to another with significant downtime, the second being that of the patients, two were 73 years old, one was 79

years old and one was 56 years old. The septuagenarians all reported significant difficulties with using the internet in general, while the 56-year-old made two JointPRO accounts, registering two separate email addresses, but did not complete a test via either account. So as to not lose the opportunity to capture their data, each subject was telephoned and completed the questionnaires over the phone. They were read the questions exactly as worded on the official Oxford Knee Score (appendix Figure 13.7) and EQ-5D 5L (appendix Figure 13.8) paper surveys, onto which the results were transcribed. In so doing, the maximum time between gait analysis and telephone-assisted PROMs scoring were 3 weeks. The limitations of this are discussed at the end of the chapter.

7.3.4 Statistical Analysis

Scores were collated in SPSS V27(IBM). Subject demographics were analysed by ANOVA (significance $p<0.05$). PROMs data were not normally distributed and were, therefore, analysed by Kruskal-Wallis and Mann-Whitney test (significance $p<0.05$) where differences were found. Data were analysed by overall score, then by individual question or domain. Individual questions were compared using mean values, in order to compare MCIDs. The limitations of this are discussed later.

There is evidence that patient satisfaction following TKA wains with time, peaking two years following surgery[216]. The distribution of mean OKS and EQ-5D with time following all CPKA and staged CPKA is compared graphically with TKA in months post-surgery, to determine whether the benefits of PROMs appear to be sustained following surgery.

7.4 Results

7.4.1 The subjective outcomes of Combined Partial Knee Arthroplasty (primary and staged)

OKS and EQ-5D scores were completed by 52 (87%) of CPKA subjects (primary and staged) from gait Study 1. The 8 scores not collected were all from primary BCA-L subjects (7 patients, 8 knees). All 28 TKA subjects in Study 1 returned scores. In the 'All CPKA' group, 38 (73%) patients completed online surveys via JointPRO whilst 10 (19%) patients completed paper-based scores, the remaining 4 (8%) patients completed the scores over the telephone (2 primary Bi-UKA and 2 staged Bi-UKA patients). In the TKA group, 18 (64%) subjects completed online scores via JointPRO with the remaining 10 (36%) subjects completing paper-based scores.

For the OKS, mean and median scores were significantly higher for CPKA than for TKA (mean 4.5 points, median 4.0 points, p<0.002, Table 7.1, Figure 7.3) though this did not exceed the minimum significance of 5 points. Similarly, CPKA recorded a significantly higher mean and median EQ-5D than TKA (p≤0.01, Table 7.1, Figure 7.3).

STUDY 1	All CPKA	TKA	Difference	p value
Number of Knees (n =)	52	28		
Sex: M:F (% male)	21 : 31 (40%)	12 : 16 (43%)		0.8
Age (Years)	67 ± 10	67 ± 9		0.8
Body Mass Index (kg/m²)	27 ± 5	27 ± 4		0.9
Mean Months Post-Surgery (SD)	21 ± 18	46 ± 48	**25**	**0.001**
Median Months Post-Surgery (Range)	14 (4 – 81)	21 (6 – 150)	7	0.3
OKS Mean	40.7 ± 6.6	36.2 ± 5.8	4.5	**0.001**
OKS Median (Interquartile Range)	42 (38 – 46)	38 (32 – 40)	4	**0.002**
EQ-5D Mean	0.91 ± 0.08	0.78 ± 0.14	0.13	**<0.001**
EQ-5D Median (interquartile Range)	0.94 (0.84 – 0.95)	0.83 (0.73 0.89)	0.12	**0.01**

Table 7.1 Patient reported outcomes following Combined Partial Knee Arthroplasty (CPKA) subjects (Study 1) compared to healthy controls and Total Knee Arthroplasty (TKA) subjects. Demographics are means with standard deviations unless otherwise stated, compared with ANOVA, Sex compared with a Chi-Square test. PROMs are mean variables subject to Kruskal-Wallis then Mann-Whitney Test. Medians test where specified. All tests, significance p <0.05.

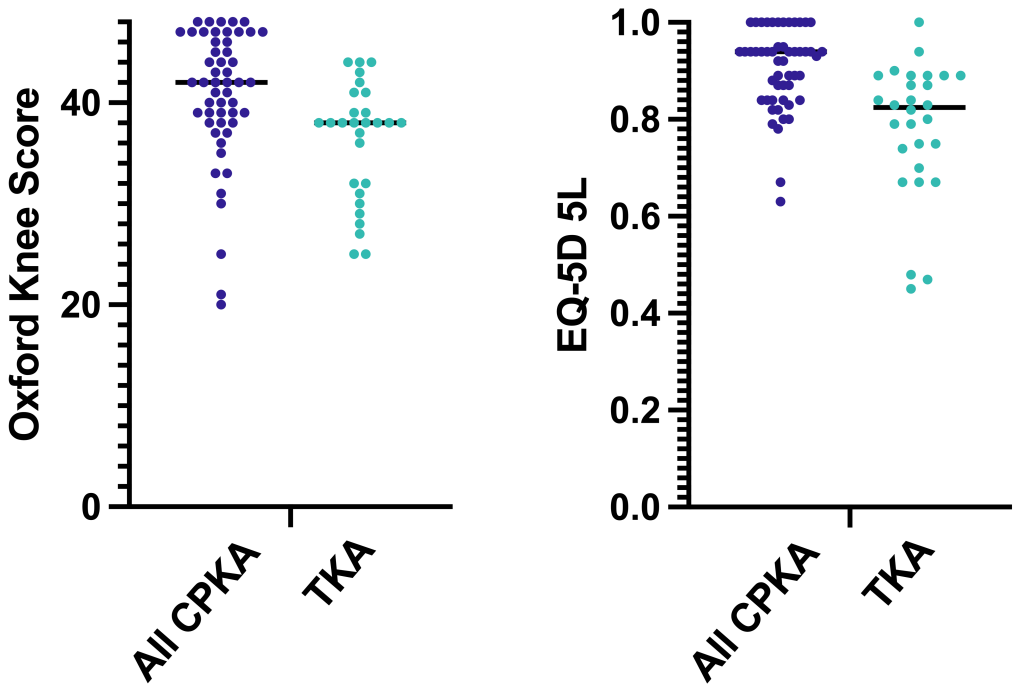


Figure 7.3. Median Oxford Knee score and EuroQol-5D (EQ-5D) for all Combined Partial Knee Arthroplasty (CPKA) subjects (n=52) compared to total knee arthroplasty (TKA) subjects (n=28). Black line represents the median score, with individual points for each subject.

The proportion of subjects in the 'All CPKA' group scoring 'excellent' OKS Scores (≥41) were 57% (n=31) compared to 25% (n=7) TKAs. Of note, 8 CPKA subjects scored 47 points and 4 subjects scored 48 points. No patients in the TKA cohort scored 47 or 48 points, the highest score being 44 points. Three patients in the CPKA group (6%) and three patients in the TKA group (11%) had a 'poor' outcome on the OKS (<21 points). The lowest score in the CPKA group were 20, compared to 25 in the TKA group.

Though not validated by individual question, it is noteworthy that CPKA scored equal to or higher than TKA in all questions of the OKS except question 2 (Table 7.2), with significant differences seen in use of transport, sit-to-stand, kneeling, instability symptoms and stair descent.

STUDY 1	CPKA	TKA	Dif	p value
Overall Mean OKS (SD)	40.7 ± 6.6	36.2 ± 5.8	4.5	**0.001**
Q1. How would you describe the Pain you usually have from your knee?	2.9 ± 1.0	2.8 ± 1.1	0.1	0.7
Q2. Have you had any trouble with washing and drying yourself (all over) because of your knee?	3.7 ± 0.7	3.8 ± 0.4	-0.1	0.4
Q3. Have you had any trouble getting in or out of the car or using public transport because of your knee?	3.3± 0.8	2.7 ± 0.9	0.6	**0.002**
Q4. For how long have you been able to walk before pain from your knee becomes severe?	3.7 ± 0.9	3.5 ± 0.8	0.2	0.7
Q5. How painful has it been for you to stand up from a chair because of your knee?	3.3 ± 0.9	2.9 ± 0.8	0.4	**0.01**
Q6. Have you been limping when walking because of your knee?	3.3 ± 0.9	3.0 ± 1.1	0.3	0.2
Q7. Could you kneel down and get up again afterwards?	2.7 ± 1.2	1.6 ± 0.9	1.1	**<0.001**
Q8. Have you been troubled by pain from your knee in bed at night?	3.4 ± 0.8	3.1 ± 1.0	0.3	0.2
Q9. How much has pain from your knee interfered with your usual work?	3.5 ± 0.7	3.4 ± 0.9	0.1	1.0
Q10. Have you felt that your knee may suddenly 'give way' or let you down?	3.7 ± 0.6	2.9 ± 0.8	0.8	**<0.001**
Q11.Could you do the household shopping on your own?	3.7 ± 0.8	3.5 ± 1.1	0.2	0.7
Q12. Could you walk down one flight of stairs?	3.5 ± 0.7	3.1 ± 0.8	0.4	**0.004**

Table 7.2. Oxford Knee Scores between all CPKA and TKA groups by overall score, where 48 is the best possible outcome, and by individual question. Individual question has a maximum score of 4 for best outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Differences (CPKA – TKA) are shown, with significant differences ($p<0.05$) highlighted in bold.

Mean EQ-5D were higher for CPKA compared to TKA ($p<0.02$, Table 7.1, Figure 7.3) EQ-5D subjects recorded scores closer to 1 in every domain (Table 7.3), reaching significance in all domains except anxiety (all $p\leq0.01$).

STUDY 1	All CPKA	TKA	Difference	p value
Overall Mean EQ5D (SD)	0.91 ± 0.08	0.78 ± 0.14	0.13	**<0.001**
Mobility	1.4 ± 0.7	2.3 ± 0.9	0.9	**<0.001**
Self-Care	1.1 ± 0.4	1.4 ± 0.6	0.3	**0.01**
Usual Activities	1.5 ± 0.7	2.4 ± 1.0	0.5	**<0.001**
Pain	1.8 ± 0.7	2.4 ± 0.7	0.6	**0.002**
Anxiety	1.2 ± 0.4	1.3 ± 0.7	0.1	0.3

Table 7.3. Euro-Qol 5D Scores between all CPKA subjects and a matched TKA group by overall score and by individual domain. The best possible outcome for the overall score is 1. Each domain is graded 1-5 where 1 is the best overall outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold

7.4.2 The subjective outcomes of Medial Bicompartmental Arthroplasty

7.4.2.1 Publication

This section includes text and images from the following publication, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. Medial bicompartmental arthroplasty patients display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients. Knee Surg Sports Traumatol Arthrosc. 2021 Oct 23. doi: 10.1007/s00167-021-06773-8

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7.4.2.2 Patients

OKS and EQ-5D scores were completed by all arthroplasty subjects in Study 2. In the BCA-M group, 10 patients completed online surveys via JointPRO whilst 6 patients completed paper-based scores. In the TKA group, 12 subjects completed online scores via JointPRO with the remaining 8 subjects completing paper-based scores.

7.4.2.3 Results

BCA-M recorded a significantly higher mean than TKA with a difference of 5.4 ($p<0.02$, Table 7.4), exceeding the MCID. Median OKS scores were also significantly higher for BCA-M than TKA with a difference of 3 points ($p=0.02$, Table 7.4, Figure 7.4), though not exceeding the MCID.

BCA-M recorded a significantly higher mean EQ-5D than TKA with a difference of 0.12 (Table 7.4, $p<0.01$). Median differences were less but remained significant (0.07 points, $p=0.02$, Table 7.4, Figure 7.4).

STUDY 2	**Primary BCA-M**	**TKA**	**Difference**	**p value**
Number of Knees (n =)	16	20		
Sex: M:F (% male)	6 : 10 (38%)	7 : 13 (35%)	3%	1
Age (Years)	68 ± 8.1	65 ± 9.9	3	0.4
Body Mass Index (kg/m^2)	26.9 ± 5.1	27.2 ± 3.9	0.3	1
Mean Months Post-Surgery (SD)	21 ± 18	40.6 ± 43	19.6	0.1
Median Months Post-Surgery (Range)	13 (6 – 65)	19.5 (6 – 147)	6.5	0.5
OKS Mean	41.4 ± 5	36.0 ± 6.5 [c]	**5.4**	**0.02**
OKS Median (Interquartile Range)	41 (38.8 – 45.5)	38 (30.5 – 41) [c]	3	**0.02**
EQ-5D Mean	0.89 ± 0.07	0.77 ± 0.16 [c]	0.12	**0.01**
EQ-5D Median (interquartile Range)	0.88 (0.84 – 0.94)	0.81 (0.73 – 0.89) [c]	0.07	**0.02**

Table 7.4. Patient reported outcomes following Combined Partial Knee Arthroplasty (CPKA) subjects (Study 1) compared to healthy controls and Total Knee Arthroplasty (TKA) subjects. Demographics are means with standard deviations unless otherwise stated, compared with ANOVA, Sex compared with a Chi-Square test. PROMs are mean variables subject to Kruskal-Wallis then Mann-Whitney Test. Medians test where specified. All tests, significance $p<0.05$.

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The proportion of subjects in the 'Primary BCA-M' group scoring 'excellent' OKS Scores (≥41) were 50% (n = 8) compared to 30% (n = 6) TKAs. Of note, 2 CPKA subjects scored 47 points and 2 subjects scored 48 points. No patients in the TKA cohort scored 47 or 48 points, the highest score being 44 points. No patient in either group had a 'poor' outcome (OKS <21 points). The lowest score in the Primary BCA-M group were 30, compared to 25 in the TKA group.

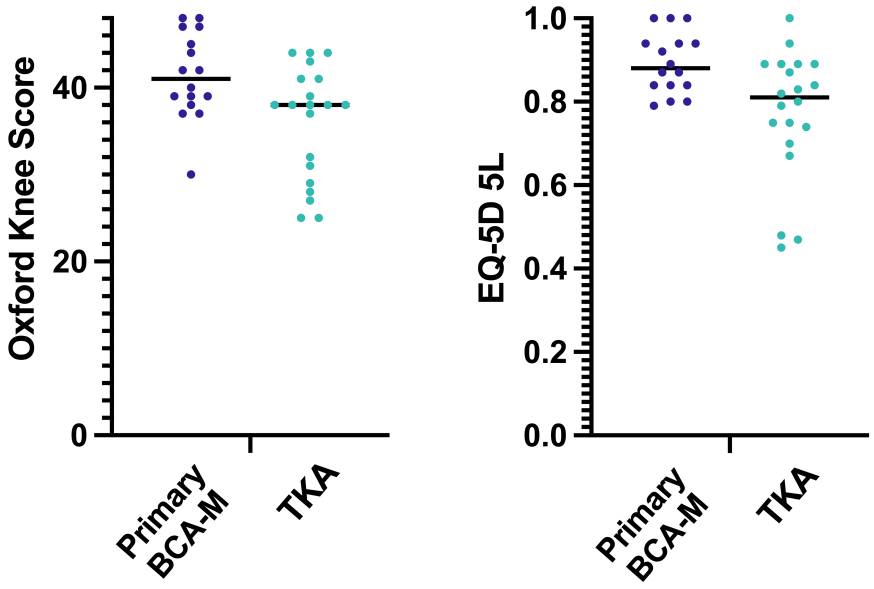


Figure 7.4. Median Oxford Knee score and EuroQol-5D (EQ-5D) for medial bicompartmental arthroplasty (BCA-M) compared to total knee arthroplasty (TKA). Black line represents the median score, with individual points for each subject

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Though not validated by individual question, it is noteworthy that BCA-M scored higher than TKA in all questions of the OKS except question 1 (Table 7.5), with significant differences seen in use of transport, sit-to-stand, kneeling, instability symptoms and use of the stairs.

Study 2	Primary BCA-M	TKA	Difference	p value
Overall OKS	41.4 ± 5	36.0 ± 6.5	5.4	**0.016**
Q1. How would you describe the Pain you usually have from your knee?	2.8 ± 1.1	2.8 ± 1.1	0	1
Q2. Have you had any trouble with washing and drying yourself (all over) because of your knee?	3.8 ± 0.5	3.8 ± 0.4	0.1	0.4
Q3. Have you had any trouble getting in or out of the car or using public transport because of your knee?	3.3 ± 0.8	2.6 ± 1.0	0.7	**0.02**
Q4. For how long have you been able to walk before pain from your knee becomes severe?	3.8 ± 0.5	3.4 ± 0.9	0.5	0.07
Q5. How painful has it been for you to stand up from a chair because of your knee?	3.4 ± 0.8	2.8 ± 0.7	0.6	**0.01**
Q6. Have you been limping when walking because of your knee?	3.6 ± 0.6	3.1 ± 1.0	0.5	0.2
Q7. Could you kneel down and get up again afterwards?	2.8 ± 1.2	1.6 ± 1.0	1.3	**0.002**
Q8. Have you been troubled by pain from your knee in bed at night?	3.3 ± 0.8	3.2 ± 1.0	0.1	0.9
Q9. How much has pain from your knee interfered with your usual work?	3.6 ± 0.5	3.1 ± 0.8	0.3	0.8
Q10. Have you felt that your knee may suddenly 'give way' or let you down?	3.6 ± 0.5	3.1 ± 0.8	0.6	**0.03**
Q11.Could you do the household shopping on your own?	3.9 ± 0.3	3.4 ± 1.3	0.5	0.3
Q12. Could you walk down one flight of stairs?	3.7 ± 0.8	3.1 ± 0.9	0.6	**0.005**

Table 7.5. Oxford Knee Scores between Primary BCA-M and TKA groups by overall score, where 48 is the best possible outcome, and by individual question. Each question has a maximum score of 4 for best outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.

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BCA-M subjects recorded scores closer to 1 in every domain of the EQ-5D 5L (Table 7.6), reaching significance in mobility, usual activities and pain (all p<0.006).

	BCA-M	TKA	Difference	p value
Overall EQ5D	0.89 ± 0.07	0.77 ± 0.16	0.12	**0.012**
Mobility	1.5 ± 0.7	2.5 ± 1.0	0.95	**0.004**
Self-Care	1.1 ± 0.3	1.4 ± 0.7	0.34	0.07
Usual Activities	1.6 ± 0.7	2.6 ± 1.1	0.99	**0.005**
Pain	1.9 ± 0.6	2.4 ± 0.7	0.53	**0.02**
Anxiety	1.2 ± 0.4	1.3 ± 0.7	0.11	0.8

Table 7.6. Euro-Qol 5D Scores between primary BCA-M subjects and a matched TKA group by overall score and by individual domain. The best possible outcome for the overall score is 1. Each domain is graded 1-5 where 1 is the best overall outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.

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7.4.3 The subjective outcomes of lateral bicompartmental arthroplasty

OKS and EQ-5D scores were completed by just 5 primary BCA-L subjects (6 knees) from Study 3. All patients were female. The patient with bilateral BCA-L completed separate scores for each knee. One subject completed a paper score, the remaining 5 scores were recorded on JointPRO. All TKA subjects in the study completed scores, 12 on JointPRO, 7 on paper. Since numbers in the BCA-L group are so low, they are written here for interest, (no known other dataset in this regard exists in the scientific literature) rather than for any meaningful comparison, therefore a TKA group is not included. One unilateral BCA-L subject scored 21 points on the OKS, whereas scores for the other 5 knees were all equal to or greater than 41 points. The same patient scored 0.88 on the EQ-5D 5L. Overall mean and median scores are shown in Table 7.7 and the median scores in Figure 7.5.

STUDY 3	**Primary BCA-L**
Number of Patients (n =)	5
Number of Knees (n =)	6
Sex: M : F (% male)	0 : 5 (0%)
Mean Age (Years)	67 ± 7
Mean Body Mass Index (kg/m^2)	24.3 ± 3.0
Mean Months Post-Surgery (SD)	10.7 ± 5.3
Median Months Post-Surgery (Range)	11 ± 5
OKS Mean	40 ± 10
OKS Median (Interquartile Range)	42.5 (41.3 – 45.3)
EQ-5D Mean	0.92 ± 0.1
EQ-5D Median (interquartile Range)	0.92 (0.88 – 0.99)

Table 7.7. Patient reported outcomes for Primary lateral bicompartmental arthroplasty (BCA-L)

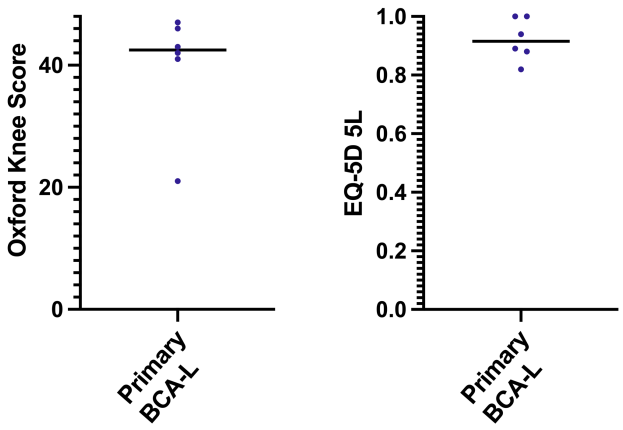


Figure 7.5. Median Oxford Knee Scores and EQ-5D 5L Scores for Primary lateral bicompartmental arthroplasty procedures (n=6)

7.4.4 The subjective outcomes of Bi-Unicondylar Arthroplasty

OKS and EQ-5D scores were completed by all arthroplasty subjects in Study 4 (primary and staged Bi-UKA). In the Bi-UKA group, 16 patients completed online surveys via JointPRO, 2 patients completed paper-based scores and the remaining 4 completed scores over the telephone. In the TKA group, 15 subjects completed online scores via JointPRO with the remaining 7 subjects completing paper-based scores.

The Bi-UKA study group returned higher mean (p=0.004) and median (p=0.007) OKS scores (Table 7.8, Figure 7.6). The rounded mean difference of 4.9 points approximates to the minimum important clinical difference, though this is not the case for median scores (4-point difference, p=0.007).

Bi-UKA subjects reported 0.11 points higher overall mean and median EQ-5D 5L, compared to TKA (p≤0.003, Figure 7.6, Table 7.8).

STUDY 4	**Bi-UKA (Primary and Staged)**	**TKA**	**Difference**	**p value**
Number of Knees (n =)	22	22	0	
Sex: M:F (% male)	14 : 8 (64%)	12 : 10 (55%)	9%	0.7
Age (Years)	68 ± 13	67 ± 10	1	0.8
Body Mass Index (kg/m²)	28 ± 5	27 ± 4	1	0.5
Mean Months Post-Surgery (SD)	23 ± 20	52 ± 51	**29**	**0.02**
Median Months Post-Surgery (Range)	17 (8 – 33)	24 (16 – 76)	7	0.2
OKS Mean	40.9 ± 7.1	36.0 ± 5.3	4.9	**0.004**
OKS Median (Interquartile Range)	42 (38 – 47)	38 (31 – 39)	4	**0.007**
EQ-5D Mean	0.91 ± 0.1	0.80 ± 0.1	0.11	**<0.001**
EQ-5D Median (interquartile Range)	0.94 (0.88 – 0.95)	0.83 (0.74 – 0.89)	0.11	**0.003**

Table 7.8. Patient reported outcomes following Bi-Unicondylar Arthroplasty (primary and staged Bi-UKA) subjects (Study 1) compared to healthy controls and Total Knee Arthroplasty (TKA) subjects. Demographics are means with standard deviations unless otherwise stated, compared with ANOVA, Sex compared with a Chi-Square test. PROMs are mean variables subject to Kruskal-Wallis then Mann-Whitney Test. Median test where specified. All tests, significance p <0.05. [354]

The proportion of subjects in the Bi-UKA (primary and staged) group scoring 'excellent' OKS Scores (≥41) were 59% (n=13) compared to 18% (n=4) TKAs. Of note, 4 Bi-UKA subjects scored 47 points and 3 subjects scored 48 points. No patients in the TKA cohort scored 47 or 48 points, the highest

score being 44 points. One patient in each group (5%) had a 'poor' outcome on the OKS (<21 points). The lowest score in the Bi-UKA group were 20, compared to 25 in the TKA group.

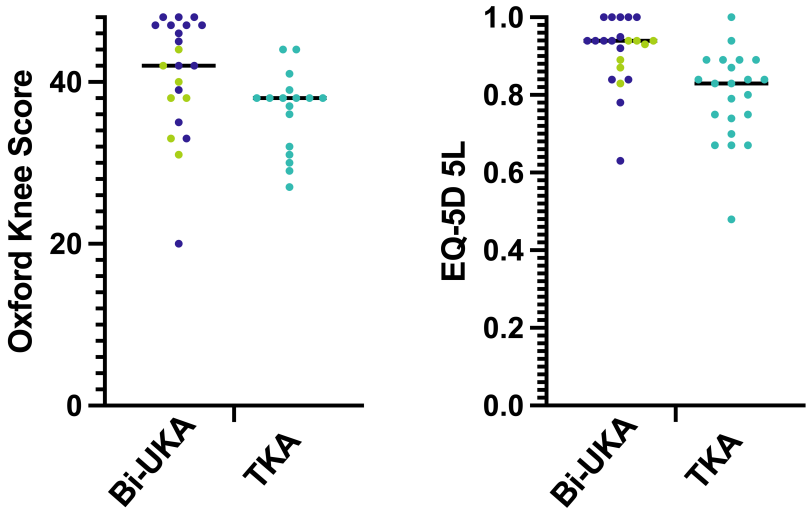


Figure 7.6. Median Oxford Knee score and EuroQol-5D (EQ-5D) for all Bi-Unicondylar Arthroplasty (Bi-UKA) subjects compared to total knee arthroplasty (TKA). Black line represents the median score, with individual points for each subject. Bi-UKA group differentiates subjects by subgroup: primary Bi-UKA (green), staged Bi-UKA (dark purple).[354]

Though not validated by individual question, it is noteworthy that Bi-UKA scored equal to or higher than TKA in all questions of the OKS, with significant differences seen in use of transport, sit-to-stand, kneeling, instability symptoms and use of the stairs (Table 7.9).

Study 4	All Bi-UKA	TKA	Difference	p value
Overall OKS	40.9 ± 7.1	36 ± 5.3	**4.9**	**0.004**
Q1. How would you describe the Pain you usually have from your knee?	2.9 ± 1.0	2.5 ± 1.2	0.4	0.4
Q2. Have you had any trouble with washing and drying yourself (all over) because of your knee?	3.8 ± 0.5	3.8 ± 0.4	0	0.5
Q3. Have you had any trouble getting in or out of the car or using public transport because of your knee?	3.4 ± 0.7	2.7 ± 0.9	**0.7**	**0.008**
Q4. For how long have you been able to walk before pain from your knee becomes severe?	3.6 ± 0.8	3.4 ± 0.8	0.2	0.2
Q5. How painful has it been for you to stand up from a chair because of your knee?	3.3 ± 0.8	2.7 ± 0.9	**0.6**	**0.03**
Q6. Have you been limping when walking because of your knee?	3.3 ± 0.9	2.9 ± 1.1	0.4	0.2
Q7. Could you kneel down and get up again afterwards?	2.5 ± 1.2	1.7 ± 1.0	**0.8**	**0.03**
Q8. Have you been troubled by pain from your knee in bed at night?	3.5 ± 0.8	3.0 ± 1.0	0.5	0.2
Q9. How much has pain from your knee interfered with your usual work?	3.6 ± 0.7	3.4 ± 0.9	0.2	0.4
Q10. Have you felt that your knee may suddenly 'give way' or let you down?	3.6 ± 0.8	3.1 ± 0.8	**0.5**	**0.008**
Q11.Could you do the household shopping on your own?	3.8 ± 0.6	3.6 ± 1.0	0.2	0.7
Q12. Could you walk down one flight of stairs?	3.5 ± 0.7	3.0 ± 0.8	**0.5**	**0.01**

Table 7.9. Oxford Knee Scores between Bi-Unicondylar Arthroplasty (Primary and Staged Bi-UKA) and TKA groups by overall score, where 48 is the best possible outcome, and by individual question. Each question has a maximum score of 4 for best outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.[354]

Bi-UKA subjects recorded scores closer to 1 in every domain of the EQ-5D 5L (Table 7.10), reaching significance in mobility, usual activities and pain (all p≤0.007).

STUDY 4	Bi-UKA (Primary and Staged)	TKA	Difference	p value
Overall EQ5D	0.91 ± 0.1	0.80 ± 0.1	**0.11**	**<0.001**
Mobility	1.4 ± 0.7	2.2 ± 0.8	**0.8**	**0.001**
Self-Care	1.2 ± 0.5	1.4 ± 0.6	0.2	0.2
Usual Activities	1.4 ± 0.6	2.1 ± 0.9	**0.7**	**0.004**
Pain	1.9 ± 0.7	2.5 ± 0.6	**0.6**	**0.007**
Anxiety	1.2 ± 0.5	1.4 ± 0.7	0.2	0.5

Table 7.10. Euro-Qol 5D Scores between Bi-Unicondylar (Primary and Staged Bi-UKA) subjects and a matched TKA group by overall score and by individual domain. The best possible outcome for the overall score is 1. Each domain is graded 1-5 where 1 is the best overall outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.[354]

7.4.5 The subjective outcomes of Staged Bi-Unicondylar Arthroplasty

7.4.5.1 Publication

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Garner AJ, Dandridge OW, Amis AA, Cobb JP, van Arkel RJ. Bi-unicondylar arthroplasty : a biomechanics and clinical outcomes study. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

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7.4.5.2 Patients

As the largest staged subgroup, OKS and EQ-5Ds for Staged Bi-UKA have been analysed separately Table 7.11. All subjects completed scores. In the staged Bi-UKA group, 12 patients completed online surveys via JointPRO whilst 1 patient completed paper-based scores and 1 patient completed scores over the telephone. In the TKA group, 14 subjects completed online scores via JointPRO with the remaining 5 subjects completing paper-based scores.

STUDY 5	**Staged Bi-UKA**	**TKA**	**Difference**	**p value**
Number of Knees (n =)	15	19	4	
Sex: M:F (% male)	10 : 5 (67%)	12 ± 7 (63%)	4%	0.8
Age (Years)	71 ± 10	69 ± 10	2	0.5
Body Mass Index (kg/m^2)	28.2 ± 5.4	27.6 ± 3.7	0.6	0.7
Mean Months Post-Surgery (SD)	22 ± 22 [b]	51 ± 52 [b]	29	0.06
Median Months Post-Surgery (Range)	17 (5 – 81)	24 (6 – 150)	7	0.7
OKS Mean	42.3 ± 8 [b]	36.8 ± 5 [b]	5.5	**0.002**
OKS Median (Interquartile Range)	46 (40.5 - 47) [b]	38 (34 – 38.5) [b]	8	**0.002**
EQ-5D Mean	0.92 ± 0.1 [b]	0.82 ± 0.1 [b]	0.1	**0.004**
EQ-5D Median (interquartile Range)	0.94 (0.88 – 1) [b]	0.84 (0.77 - 0.89) [b]	0.1	**0.004**

Table 7.11. Patient reported outcomes following staged Bi-Unicondylar (Bi-UKA) subjects (Study 5) compared to healthy controls and Total Knee Arthroplasty (TKA) subjects. Demographics are means with standard deviations unless otherwise stated, compared with ANOVA, Sex compared with a Chi-Square test. PROMs are mean variables subject to Kruskal-Wallis then Mann-Whitney Test. Medians test where specified. All tests, significance p <0.05.

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7.4.5.3 Results

The staged Bi-UKA cohort reported a mean OKS 5.5 points higher than their matched TKA counterparts (p=0.002, Table 7.11), with median scores 8 points higher (p=0.002).

The proportion of subjects in the 'Staged Bi-UKA' group scoring 'excellent' OKS Scores (≥41) were 73% (n=11) compared to 21% (n=4) TKAs. Of note, 4 Staged Bi-UKA subjects scored 47 points and 3 subjects scored 48 points. No patients in the TKA cohort scored 47 or 48 points, the highest score being 44 points. One staged Bi-UKA patient (7%) had a 'poor' outcome on the OKS (<21 points), whereas no TKAs had a poor outcome. The lowest score in the staged Bi-UKA group were 20, compared to 29 in the TKA group.

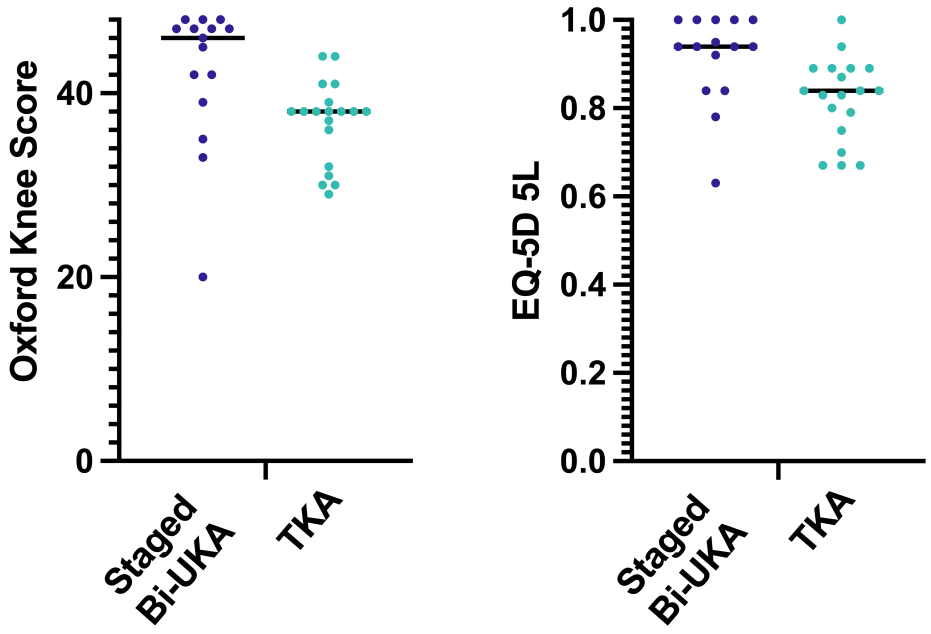


Figure 7.7. Median Oxford Knee score and EuroQol-5D (EQ-5D) for staged Bi-Unicondylar Arthroplasty (Bi-UKA) subjects compared to total knee arthroplasty (TKA). Black line represents the median score, with individual points for each subject.

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Staged Bi-UKA scored equal to or higher than TKA in all questions of the OKS with the exception of questions 2 and 11, where in both cases, TKA were 0.1 point higher (Table 7.12). Significant differences were seen in use of transport, sit-to-stand, kneeling, instability symptoms and use of the stairs (all p<0.05).

Study 4	Bi-UKA (Staged)	TKA	Difference	p value
Overall Mean OKS	42.3 ± 7.8	36.8 ± 4.5	**5.5**	**0.002**
Q1. How would you describe the Pain you usually have from your knee?	3.1 ± 1.0	2.5 ± 1.2	0.6	0.2
Q2. Have you had any trouble with washing and drying yourself (all over) because of your knee?	3.7 ± 0.6	3.8 ± 0.4	0.1	0.7
Q3. Have you had any trouble getting in or out of the car or using public transport because of your knee?	3.6 ± 0.6	2.8 ± 1.0	**0.8**	**0.01**
Q4. For how long have you been able to walk before pain from your knee becomes severe?	3.6 ± 0.8	3.5 ± 0.7	0.1	0.2
Q5. How painful has it been for you to stand up from a chair because of your knee?	3.4 ± 0.8	2.8 ± 0.9	**0.6**	**0.047**
Q6. Have you been limping when walking because of your knee?	3.4 ± 1.1	2.8 ± 1.2	0.6	0.1
Q7. Could you kneel down and get up again afterwards?	2.9 ± 1.1	1.8 ± 1.0	**1.1**	**0.01**
Q8. Have you been troubled by pain from your knee in bed at night?	3.6 ± 0.7	3.2 ± 1.0	0.4	0.1
Q9. How much has pain from your knee interfered with your usual work?	3.6 ± 0.8	3.6 ± 0.6	0	0.5
Q10. Have you felt that your knee may suddenly 'give way' or let you down?	3.7 ± 0.8	3.1 ± 0.7	**0.6**	**0.002**
Q11.Could you do the household shopping on your own?	3.8 ± 0.6	3.9 ± 0.3	0.1	0.8
Q12. Could you walk down one flight of stairs?	3.6 ± 0.7	3.0 ± 0.8	**0.6**	**0.02**

Table 7.12. Oxford Knee Scores between Bi-Unicondylar Arthroplasty (Primary and Staged Bi-UKA) and TKA groups by overall score, where 48 is the best possible outcome, and by individual question. Each question has a maximum score of 4 for best outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.

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Mean and Median EQ-5D were higher for staged Bi-UKA compared to TKA (p=0.004, Table 7.11, Figure 7.7). Staged Bi-UKA subjects recorded scores closer to 1 in every domain (Table 7.13), reaching significance in mobility, usual activities and pain (all p≤0.04).

STUDY 5	Staged Bi-UKA	TKA	Difference	p value
Overall Mean EQ5D	0.92 ± 0.1	0.82 ± 0.1	**0.1**	**0.004**
Mobility	1.40 ± 0.7	2.05 ± 0.7	**0.65**	**0.009**
Self-Care	1.20 ± 0.6	1.26 ± 0.5	0.06	0.4
Usual Activities	1.40 ± 0.6	1.95 ± 0.8	**0.55**	**0.04**
Pain	1.60 ± 0.6	2.37 ± 0.6	**0.77**	**0.002**
Anxiety	1.20 ± 0.6	1.37 ± 0.7	0.17	0.4

Table 7.13. Euro-Qol 5D Scores between staged Bi-UKA subjects and a matched TKA group by overall score and by individual domain. The best possible outcome for the overall score is 1. Each domain is graded 1-5 where 1 is the best overall outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.

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7.4.6 The subjective outcomes of Staged Combined Partial Knee Arthroplasty

7.4.6.1 Publication

This chapter includes text and images from the following publication, some of which is reproduced exactly, with permission:

Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. The compartmental approach to revision of partial knee arthroplasty results in nearer-normal gait and improved patient reported outcomes compared to total knee arthroplasty. Knee Surg Sports Traumatol Arthrosc. 2021 Aug 20. doi: 10.1007/s00167-021-06691-9.

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7.4.6.2 Patients

OKS and EQ-5D scores were completed by all arthroplasty subjects in Study 6 (6.14). In the staged CPKA group, 19 patients completed online surveys via JointPRO, 2 patients completed paper-based scores and 2 patients completed telephone scores. In the TKA group, 17 subjects completed online scores via JointPRO with the remaining 6 subjects completing paper-based scores.

7.4.6.3 Results

For the OKS, mean and median scores were significantly higher for staged CPKA than for TKA ($p \leq 0.008$, Table 7.14, Figure 7.8). Median OKS differences reached the minimum clinically important difference of 5 points, though the mean scores fell short at 4.2 points. Mean and median EQ-5D 5L scores were both significantly better for staged CPKA than for TKA ($p \leq 0.008$, Table 7.14, Figure 7.8)

STUDY 6	Staged CPKA	TKA	Difference	p value
Number of Knees (n =)	23	23	0	
Sex: M:F (% male)	11 : 12 (48%)	10 : 13 (43%)	5%	1.0
Age (Years)	68 ± 10	68 ± 10	0	0.9
Body Mass Index (kg/m^2)	28.4 ± 5.4	28.7 ± 3.5	0.3	0.8
Mean Months Post-Surgery (SD)	22 ± 21	42 ± 50	**20**	**0.08**
Median Months Post-Surgery (Range)	17 (4 – 81)	16 (6 – 150)	1	0.6
OKS Mean	41.3 ± 7.4	37.1 ± 5.1	4.2	**0.002**
OKS Median (Interquartile Range)	43 (39 – 47)	38 (32-41)	5	**<0.0001**
EQ-5D Mean	0.91 ± 0.1	0.83 ± 0.1	0.08	**0.004**
EQ-5D Median (interquartile Range)	0.94 (0.87 – 1.0)	0.84 (0.80 – 0.89)	0.1	**0.008**

Table 7.14. Patient reported outcomes following Staged Combined Partial Knee Arthroplasty (Staged CPKA) subjects (Study 6) compared to healthy controls and Total Knee Arthroplasty (TKA) subjects. Demographics are means with standard deviations unless otherwise stated, compared with ANOVA, Sex compared with a Chi-Square test. PROMs are mean variables subject to Kruskal-Wallis then Mann-Whitney Test. Medians test where specified. All tests, significance p <0.05.

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The proportion of subjects in the 'Staged CPKA' group scoring 'excellent' OKS Scores (≥41) were 48% (n=11) compared to 17% (n=4) TKAs. Of note, 4 staged CPKA subjects scored 47 points and 3 subjects scored 48 points. No patients in the TKA cohort scored 47 or 48 points, the highest score being 44 points. One patient in the staged CPKA group (4%) had a 'poor' outcome on the OKS (<21 points), whereas no TKAs had poor outcomes. The lowest score in the staged CPKA group were 20, compared to 29 in the TKA group.

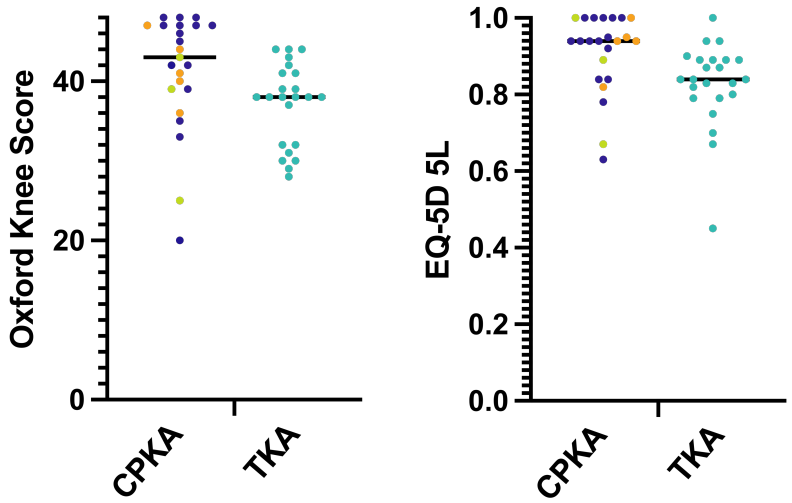


Figure 7.8. Median Oxford Knee score and EuroQol-5D (EQ-5D) for all Combined Partial Knee Arthroplasty (CPKA) subjects compared to total knee arthroplasty (TKA). Black line represents the median score, with individual points for each subject. Bi-UKA group differentiates subjects by subgroup: Staged BCA-M (orange), staged BCA-L (green), staged Bi-UKA (dark purple).

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By individual question, staged CPKA scored significantly higher in Question 2 (the use of transport); Question 7 (kneeling) and Question 10 (instability symptoms, Table 7.15). Otherwise scores were similar, with TKA 0.1 points higher in Questions 2, 9 and 11 (p=1).

Study 6	CPKA (Staged)	TKA	Difference	p value
Overall Mean OKS	41.3 ± 7.4	37.1 ± 5.1	**4.2**	**0.02**
Q1. How would you describe the Pain you usually have from your knee?	2.9 ± 1.0	2.7 ± 1.1	0.2	1
Q2. Have you had any trouble with washing and drying yourself (all over) because of your knee?	3.7 ± 0.6	3.8 ± 0.4	0.1	1
Q3. Have you had any trouble getting in or out of the car or using public transport because of your knee?	3.3 ± 0.9	2.7 ± 0.9	**0.6**	**0.027**
Q4. For how long have you been able to walk before pain from your knee becomes severe?	3.8 ± 0.6	3.6 ± 0.7	0.2	0.37
Q5. How painful has it been for you to stand up from a chair because of your knee?	3.3 ± 0.9	2.9 ± 0.8	0.4	0.11
Q6. Have you been limping when walking because of your knee?	3.4 ± 1.0	3.0 ± 1.1	0.4	0.46
Q7. Could you kneel down and get up again afterwards?	2.7 ± 1.3	1.8 ± 0.9	**0.9**	**0.02**
Q8. Have you been troubled by pain from your knee in bed at night?	3.5 ± 0.8	3.3 ± 0.8	0.2	1
Q9. How much has pain from your knee interfered with your usual work?	3.5 ± 0.9	3.6 ± 0.7	0.1	1
Q10. Have you felt that your knee may suddenly 'give way' or let you down?	3.8 ± 0.7	2.9 ± 0.8	**0.9**	**< 0.001**
Q11.Could you do the household shopping on your own?	3.7 ± 0.6	3.8 ± 0.5	0.1	1
Q12. Could you walk down one flight of stairs?	3.5 ± 0.7	3.1 ± 0.9	0.4	0.32

Table 7.15. Oxford Knee Scores between staged combined partial knee arthroplasty (staged CPKA) and TKA groups by overall score, where 48 is the best possible outcome, and by individual question. Each question has a maximum score of 4 for best outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.

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Staged CPKA subjects recorded higher mean EQ-5D than TKA (Difference 0.08, p=0.006, Table 7.16), with scores closer to 1 in mobility, usual activities, pain and anxiety, reaching significance in mobility, usual activities and pain (all p≤0.03). Median EQ-5D were higher for staged CPKA compared to TKA (p=0.008, Table 7.14, Figure 7.8).

STUDY 6	Staged Bi-UKA	TKA	Difference	p value
Overall Mean EQ5D	0.91 ± 0.1	0.83 ± 0.1	**0.08**	**0.006**
Mobility	1.4 ± 0.7	2.1 ± 0.9	**0.7**	**0.006**
Self-Care	1.2 ± 0.5	1.2 ± 0.4	0	1
Usual Activities	1.5 ± 0.7	2.1 ± 0.9	**0.6**	**0.03**
Pain	1.7 ± 0.7	2.2 ± 0.7	**0.5**	**0.03**
Anxiety	1.2 ± 0.5	1.3 ± 0.6	0.1	1

Table 7.16. Euro-Qol 5D Scores between staged CPKA subjects and a matched TKA group by overall score and by individual domain. The best possible outcome for the overall score is 1. Each domain is graded 1-5 where 1 is the best overall outcome. Values shown are means with standard deviation. Values subject to Kruskal-Willis then Mann Whitney Test with Bonferroni Correction. Significant differences are highlighted in bold.

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7.5 Discussion

Overall satisfaction and quality of life was good after all arthroplasty procedures in this investigation, including TKA (Table 7.17). All groups were, on average, within two years of surgery, though the range was out to 81 months post-operation. The minimum mean OKS were 40.7, for 'All CPKA' participants. The highest mean scores were amongst the 'Staged Bi-UKA' cohort, where mean OKS were 42.3 points, though this were the smallest group (Table 7.17). Of the median scores, the lowest scores were for the 'primary BCA-M' cohort, at 41 points, with the highest scores seen in the 'staged Bi-UKA' group. For EQ-5D, the lowest mean scores were 0.89, in the 'primary BCA-M' group, whilst the highest scores were again in the 'staged Bi-UKA' group, at 0.92 points. For median scores, all except the 'primary BCA-M' group scored median 0.94 points (Table 7.17).

Previous studies have reported higher levels of patient satisfaction following BCA-M compared to matched prospective cohorts of TKA subjects[275]. Similarly, Confalonieri et.al. reported higher satisfaction and functional scores with Bi-UKA compared to TKA[9], which are supported by the present findings. Despite undergoing more than one operation, the staged procedures reported good function on the OKS, corroborating the findings of others[293], with a good quality of life against EQ-5D.

	All CPKA	Primary BCA-M	All Bi-UKA	Staged Bi-UKA	Staged CPKA
N =	52	16	22	15	23
Mean Months (SD)	21 ± 18	21 ± 18	23 ± 20	22 ± 22	22 ± 21
Median Months (Range)	14 (4 – 81)	13 (6 – 65)	17 (8 – 33)	17 (5 – 81)	17 (4 – 81)
OKS Mean (SD)	40.7 ± 6.6	41.4 ± 5	40.9 ± 7.1	42.3 ± 8	41.3 ± 7.4
OKS Mean Difference	4.5	**5.4**	**4.9**	**5.5**	4.2
OKS Median (IQR)	42 (38 – 46)	41 (38.8 – 45.5)	42 (38 – 47)	46 (40.5 - 47)	43 (39 – 47)
OKS Median Difference	4	3	4	**8**	**5**
% Excellent (OKS ≥ 41)	57 Vs 25	50 Vs 30	59 Vs 18	73 Vs 21	48 Vs 17
% Poor (OKS < 27)	6 Vs 11	0 Vs 0	5 Vs 5	7 Vs 0	4 Vs 0
EQ-5D Mean (SD)	0.91 ± 0.08	0.89 ± 0.07	0.91 ± 0.1	0.92 ± 0.1	0.91 ± 0.1
EQ-5D Mean Difference	**0.13**	**0.12**	**0.11**	**0.1**	**0.08**
EQ-5D Median (IQR	0.94 (0.84 – 0.95)	0.88 (0.84 – 0.94)	0.94 (0.88 – 0.95)	0.94 (0.88 – 1)	0.94 (0.87 – 1.0)
EQ-5D Median Difference	**0.12**	**0.07**	**0.11**	**0.1**	**0.1**

Table 7.17. Summary of Oxford Knee Scores and EQ-5D 5L scores for all subgroups with differences between scores and those of matched TKA groups. Percentages of excellent and poor outcomes are given for the compartmental arthroplasty group Vs their matched TKA cohort. Scores exceeding the minimum important clinical difference of 5 points are highlighted in bold.

Mean OKS were between 4.2 and 5.5 points higher than TKA across all subgroups. The difference in mean OKS exceeded the reported MCID of five points[232] for the Primary BCA-M; Staged and Primary Bi-UKA and Staged Bi-UKA groups (Table 7.17). This suggests there may be an advantage in PROMs for these groups, compared to this relatively satisfied cohort of TKAs. However, it may also suggest that the groups are different, the data is potentially skewed, or that a ceiling effect is being observed. Larger cohorts are required to specifically clarify this. Despite being significantly higher, mean differences for the overall CPKA group and the staged CPKA group did not exceed five points, so for these two groups, notably the largest, conclusions beyond 'non-inferiority' are difficult to make. However, the staged CPKA did exceed the MCID in median score, as did the staged Bi-UKA subgroup, whilst the other groups did not (Table 7.17). The predicted MCID of EQ-5D 5L is widely debated, but Coretti et al. estimated it to be between 0.03 – 0.54[233]. The difference in mean and median EQ-5D scores for all groups in this study fall within this estimation. These difference are worthy of further investigation through an adequately powered study.

For each study, a higher percentage of the compartmental groups had 'excellent' OKS scores (≥41 points) with the highest percentages seen in the Bi-UKA groups. Overall, 57% of CPKA had an excellent outcome, compared to 25% of TKA, with 12 subjects scoring 47 or 48 points, compared to a maximum score of 44 in the TKA group (Table 7.17). Overall, few participants in either group recorded poor outcomes on the OKS (<27 points) and, in general, the groups were well matched for this. The lowest OKS score of the entire cohort were 20 points (Staged Bi-UKA).

The recorded OKS and EQ-5D scores are similar to widely reported literature values for UKA and TKA [216, 229, 446] with no apparent adverse effect as a consequence of the additional PKA in situ[276]. The data also suggest that, overall, the matched TKA groups were satisfied with a good quality of life, making them appropriate for comparison. This reflects the recently reported TOPKAT randomised control trial, which directly compared medial UKA with TKA[234]. At five years post UKA, OKS was mean 38.9±10.1 compared to TKA mean 37±10.6 (p=0.159) suggesting that the small sample of TKAs investigated in this thesis, is representative of much larger cohorts. Mohammad et al. reported that at 6 months post op, from a study of 38,716 propensity-matched knee replacements, OKS scores for UKA (n=19,358) and TKA (n=19,358) were 38 ± 0 9.4 and 36 ± 0.4 respectively, with 47% of UKAs reporting excellent scores (OKS ≥41 UKA Vs. 36% TKA) and poor scores (<27 points) seen in 15% Vs 16%. These scores are comparable to the findings of the current study, and suggest no adverse impact of the additional ipsilateral PKA.

Williams et. al (2013)[216] studied 5600 TKA patients over a ten-year period, reporting that maximum post-operative OKS was seen at two-years post-surgery (mean 34.4, 95% CI 33.7 - 35.2) with a gradual but significant decline thereafter. Ten-year scores were reported as 30.1 (95% CI 29.1 – 31.1). Similar studies for CPKA over time are required, when larger datasets become available.

Although not validated by question, it is noteworthy that all CPKA subgroups were advantageous over TKA for use of transport (Q3), kneeling (Q7) and instability symptoms (Q10) (Table 7.18) In all except the staged CPKA cohort, statistically significant advantages were also seen in sit-to-stand (Q5) and stair descent (Q12). These findings are noteworthy and support the concept that compartmental arthroplasty preserves isokinetic quadriceps strength[395], and extensor efficiency of the knee, giving an indication that the cadaveric data in Chapter 5, may have a bearing on clinical outcomes. ACL preservation in compartmental arthroplasty may, in part, explain differences in stability.

	OKS	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12
All CPKA													
Primary BCA-M													
All Bi-UKA													
Staged Bi-UKA													
All Staged CPKA													

Table 7.18. Summary of Reported Outcomes by Question for Oxford Knee Score. Cells in Purple demonstrate statistically significant advantage of CPKA over TKA ($p<0.05$). Blank cells indicate $p>0.05$

Regarding the EQ-5D, all groups were statistically better than TKA, with advantages seen for mobility, usual activities and pain in all groups ($p<0.05$, Table 7.19). The 'All CPKA' group were the only group to show a statistical advantage for self-care.

	Mean EQ-5D	Mobility	Self-Care	Usual Activities	Pain	Anxiety
All CPKA						
Primary BCA-M						
All Staged and Primary Bi-UKA						
Staged Bi-UKA						
All Staged CPKA						

Table 7.19. Summary of Reported Outcomes by Question for EQ-5D. Cells in Purple demonstrate a statistically significant advantage of CPKA over TKA ($p<0.05$). Blank cells indicate $p>0.05$

7.6 Limitations

The study was powered for gait analysis, with OKS and EQ-5D 5L scores collected as secondary outcome measures. The power calculation of the TOPKAT randomised control trial resolved that a sample size of 500 patients would be required to detect differences of 2 points on the OKS between medial UKA and TKA, with 80% power and 95% confidence, or 90% power for a 3-point change[234]. Considering this, the current study is underpowered for PROMs. Nonetheless, the results support the findings of gait analysis, such that neither group were disadvantaged by being dissatisfied with the outcome of their surgery.

PROMs are at their most meaningful when documented over the course of a patient's treatment; they contribute toward the decision to operate, by giving a quantifiable indication of the impact the joint disease has on the patient's quality of life, and then indicate the change as a result of surgery (for better or worse!) PROMs enable different interventions to be compared over time. Therefore, a single 'snapshot' PROM score, as reported here, is a point of interest, but has clear limitations. Each subject was asked to complete their scores at the time of treadmill assessment, but the variability in time from surgery, and lack of data from other time points, for example pre- and post-surgery, reduces the impact of the comparison. The analysis of MCID is challenging in the context of scores which demonstrate ceiling effects, as is seen here. MCIDs are most meaningful when comparing pre- and post-operative scores for each subject, so comparisons of differences between post-operative cohorts makes interpretation difficult and limits the possible conclusions.

This study utilised the OKS and EQ-5D since these are broad and capture trends across a wide spectrum of joint pathologies. However, a ceiling effect is visible in the Bi-UKA dataset (Figure 7.6, Figure 7.7) suggesting that future research may benefit from the addition of other scores less susceptible to ceiling effects.

Limitations of data collection methods must be acknowledged. Data for 7 subjects (8 knees) from the primary BCA-L group were missing, meaning comparisons with TKA were not possible for this subgroup. Four Bi-UKA (two primary, two staged) patients had their data recorded via telephone, a method against which neither the OKS nor EQ-5D have been validated. Amongst the remaining 48 CPKA subjects, 73% recorded their scores online, whilst 19% completed paper-based scores. JointPro.co.uk has been validated against the paper-based scores, and therefore theoretically there should not be any significant differences between these methods, but a potential for errors does

arise. The same were true for TKA, whereby 64% completed online scores, whilst 36% completed paper-based scores. This does raise the issue of difficulties faced by elderly subjects when using online scoring systems and perhaps the internet in general, which may lead to frustration; influence outcomes or deter some respondents.

7.7 Chapter Summary

Although only a snapshot of post-operative subjective outcomes following primary and staged CPKA, recurrent trends are seen. CPKA patients appear overall to be satisfied and report a good quality of life. This is particularly significant in those whom have undergone staged procedures, where one might expect multiple procedures to be detrimental to patient's wellbeing. In general, there does appear to be a statistical advantage of CPKA over TKA, with some procedures recording scores in excess of the minimum important clinical differences, suggesting these differences may be meaningful. An adequately powered study with pre- and post-operative data, captured at specific and comparable post-operative time periods is, therefore, warranted.

8 Drawing the Studies Together

Compartmental arthroplasty is witnessing a resurgence in popularity. Historically perceived to be a technically demanding procedure, emerging evidence is empowering surgeons to be more targeted in their approach to treatment of multi-compartment disease and once again question whether combined partial knee arthroplasty may be a viable alternative to TKA[317, 447].

This thesis began by reviewing the history of arthroplasty. With hindsight, it often becomes apparent that the original ideas are the best. Only by understanding past lessons of arthroplasty, particularly those associated with compartmental arthroplasty, may we appreciate the steps required to re-explore these early ideas and make significant improvements. The rationale for alternatives to TKA paved the way for investigation of CPKA using a three-pronged approach: in vitro, gait analysis and patient reported outcomes.

A classification system has been proposed to unify the language of compartmental arthroplasty, to improve patient safety by ensuring the patient and everyone involved in their care understand exactly which operation is being discussed and/or undertaken. Our patients regularly search the internet for information regarding their treatment options. Therefore, it is conceivable that patients and healthcare providers are misled by the confused and conflicting terminology in the literature which, at worst, could lead to significant surgical errors and/or undermine the process of informed consent. The secondary impact of unified language is research progress. If we consistently report on the outcomes of compartmental arthroplasty using common terms and accurate language, we begin to amass a body of data pertaining to their use, that is currently lacking from the literature.

The RPKC attempts to better understand headline revision rates of CPKA and PKA by classifying second surgery according to its complexity and magnitude. In so doing, common language may be used to differentiate between simple changes of bearings; the addition of second implants; revision to primary TKA and revision to complex TKA; all of which have very different implications for the patient and the surgeon.

In vivo, CPKA restored nearer-normal weight-acceptance and mid-stance forces, when the quadriceps are active[395]. This difference may be explained by differences observed in extensor function in vitro: The cadaveric model demonstrated that UKA and BCA make little impact on the efficiency of the extensor mechanism, while the negative impact of TKA on extensor function is

substantial, with a reduction in extension moment of over 40% towards terminal knee extension. Following UKA, no differences were detected in either extension moment or efficiency. The addition of a PFA resulted in a small drop in extension moment between 70-90° flexion but when examined in the context of the full range associated with the quadriceps active range of activities of daily living, extensor efficiency was largely unaffected. Conversely, following TKA, large decreases in extension moment at low angles of knee flexion resulted in 12-43% drops in extensor efficiency over ranges of knee flexion associated with common activities of daily living. This suggests that in order to achieve the same function during daily activities with a high number of cycles, including stair ascent and fast walking, TKA patients expend significantly more energy, particularly during activities associated with increased levels of quadriceps activity and high cycle numbers, such as fast walking[389, 393, 394]. This study suggests TKA patients may expend significantly more energy to achieve the same function during these activities, corroborating findings of others, who have shown abnormal flexion-extension moments following TKA, attributing this to reduced quadriceps effectiveness[395]. This finding was supported by the patient reported outcomes where differences in relation to alighting a vehicle, rising from a chair, stair descent and kneeling support the concept that CPKA preserves isokinetic quadriceps strength[395].

The anterior-posterior cadaveric study reaffirmed the knowledge that UKA-M retains near-native anterior-posterior stability in the treatment of medial compartment OA. However, for the first time, it has also provided evidence of the near-native anterior-posterior stability of UKA-L and CPKA, whereas Posterior Cruciate Ligament-preserving TKA demonstrated increased laxity, particularly in anterior tibial translation. These data support the concept that ACL preservation is critical for anterior-posterior stability and efficiency of the extensor mechanism[387], contributing to the ability to deliver quadriceps power. ACL preservation in CPKA may, in part, explain patient-reported perceived differences in stability.

The gait and cadaveric methods complement each other. The cadaveric model allowed within-specimen repeated measures analyses, eliminating confounding factors including anatomical variance or quadriceps deficiency, only varying implant state. However, this model cannot account for postoperative rehabilitation, nor does it replicate true in vivo loading or kinematics, which are inherently captured by gait measurements. Benefits for CPKA are reported in gait and patient reported outcomes, substantiated by advantageous in vitro biomechanics. These data support the concept that primary CPKA is an acceptable, cruciate ligament, peri-articular tissue and bone-preserving alternative to TKA for two-compartment arthrosis.

8.1 The case for staged compartmental arthroplasty

There is good evidence that primary PKA is safer, more cost effective and higher functioning than primary TKA[234, 413, 418, 419, 448, 449] but at the expense of persistently high revision rates. These undoubtedly deter a significant number of knee surgeons from ever performing PKA.

Progressive arthritis remains a common mode of failure following single compartment PKA[76, 189, 450]. Removal of a well-fixed PKA can result in significant bone loss, requiring increased constraint, augments, wedges and stems[147, 451-453]. The data on outcomes following revision of UKA to TKA are varied, with some studies reporting comparable rates of function and satisfaction to primary UKA[408, 454] while others report inferior outcomes compared to matched cohorts undergoing primary TKA[409]. Retention of a well-fixed, well-functioning primary PKA and targeted treatment of a newly degenerate compartment is an appealing option to PKA advocates, since the subsequent operation may be regarded as a 'second primary' procedure.

A designer series reported that the benefits of PKA persist after staged Bi-UKA, with excellent functional outcomes, faster recovery, short hospital stays and very low complication rates[293]. This suggests that conversion to CPKA may be a good option in young people keen to avoid revision to TKA at an early age, and a safer alternative in older people or those considered high surgical risk. In terms of surgical invasiveness, the compartmental approach is a relatively minor undertaking compared to revision to TKA, and may, therefore be a conservative way of satisfying the NICE guidelines. The 'compartmental approach' advocates the addition of a second PKA to the newly degenerate compartment, while retaining the primary PKA and ACL[77, 317]. Through this thesis, and the work of others, it has been shown to preserve healthy gait characteristics, maintain high levels of satisfaction and good quality of life, despite second surgery.

8.2 Summary

Knee surgery is evolving, moving away from a “one definitive procedure” approach towards a patient-safety conscious, minor surgery “as required” strategy. This thesis contributes toward the view that a compartmental approach to treatment of end-staged arthritis in a native compartment is high functioning and leads to good patient outcomes. It has the potential to support surgeons in their decision to perform primary PKA in the young, active patient, with reduced concern about subsequent surgery and the consequences of major revision. Further, it offers a safer, less invasive, bone-preserving alternative to revision to TKA in the event of progression of arthritis, which may prove particularly important in an ageing population or those who pose a high risk of medical complications.

9 Dissemination and Impact of this Work

9.1 Awards and Prizes:

May 2021: **British Association of Surgery of the Knee (BASK) Annual Conference 'Best Free Paper' Prize** £1000

May 2021: **Sam Simmond's Regional Meeting Prize** For "First place podium presentation"

Sept 2019: **International Society for Technology in Arthroplasty Young Investigator Scholarship,** for highly scoring conference abstract. $500.

Aug 2019: **British Orthopaedic Research Society / Bone & Joint Research '2019 New Investigator Award'** for conference abstract. £500.

April 2019: **European Knee Society Arthroplasty Conference 'Best Free Paper'** for Podium Presentation, Valencia, Spain. > 500 submitted abstracts, 80 podium presentations. Prize worth £250.

Mar 2019: **British Association of Surgery of the Knee (BASK) Annual Congress ePoster Prize** for best podium with ePoster presentation. £500

Dec 2018: **Highest Rated Early Career Researcher**. IMechE – Engineering the Knee Conference.

9.2 Peer-Review Publications and Book Chapters

Nov 2021: **Bi-Unicondylar Arthroplasty: A Biomechanics and Clinical Outcomes Study**. Garner, A.J. Dandridge, O.W. Amis, A.A. Cobb, J.P. van Arkel, R.J. Bone Joint Res. 2021 Nov;10(11):723-733. doi: 10.1302/2046-3758.1011.BJR-2021-0151.R1

Sept 2021: **Medial Bicompartmental Arthroplasty Patients Display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients.** Garner AJ, Dandridge OW, van Arkel RJ, Cobb JP. Knee Surg Sports Traumatol Arthrosc. 2021 Oct 23. doi: 10.1007/s00167-021-06773-8

Aug 2021: **The Compartmental Approach to Revision of Partial Knee Arthroplasty Results in Nearer-Normal Gait and Improved Patient Reported Outcomes compared to Total Knee Arthroplasty.** Garner, A. Dandridge, O. van Arkel R. Cobb, J. Knee Surgery, Sports Traumatology, Arthroscopy, 2021 Aug 20. Doi: 10.1007/s00167-021-06691-9

July 2021: **Validity of Repeated-Measures Analyses of in vitro Arthroplasty Kinematics and Kinetics.** Dandridge O, Garner A, Jeffers JRT, Amis AA, Cobb JP, van Arkel RJ. J Biomech. 2021 Aug 2;129:110669. doi: 10.1016/j.jbiomech.2021.110669.

Jun 2021: **The Revision Partial Knee Classification (RPKC) System: Understanding the causative pathology and magnitude of further surgery following partial knee arthroplasty.** Garner, A. Edwards, T. Liddle, A. Jones, G. Cobb, J. Bone & Joint Open 2021 Jun 30. doi: 10.1002/jor.25124

June 2021: **Partial and Combined Partial Knee Arthroplasty: Greater Anterior-Posterior Stability than Posterior-Cruciate Retaining Total Knee Arthroplasty.** Garner, A. Dandridge, O. Amis, A. Cobb, J. van Arkel, R.J. Journal of Arthroplasty. Doi: 10.1016. Journal of Arthroplasty 2021.06.025

June 2021: **Variation in the Patellar Tendon Moment Arm identified with an improved measurement framework.** Dandridge, O. Garner, A. Amis, A.A. Cobb, J.P. van Arkel, R.J. Journal of Orthopaedic Research doi: 10.1002/jor.25124

Jan 2021: **The Extensor Efficiency of Unicompartmental, Bicompartmental and Total Knee Arthroplasty.** Garner, A. Dandridge, O. Amis, A. Cobb, J. van Arkel, R. Bone & Joint Res 2021;10(1):1-9 doi: 10.1302/2046-3758.101.BJR- 2020-0248.R1

Nov 2020: **The Compartmental Distribution of Knee Osteoarthritis – a Systematic Review and Meta-Analysis**. Stoddart, J. Dandridge, O. Garner, A. Cobb, J. van Arkel, R. Osteoarthritis and Cartilage. 2020 Nov 27. Epub 2020/12/01.

July 2020: **Combined Partial Knee Replacement**: Garner, A. Cobb, J. **Book Chapter**. Personalized Hip and Knee Replacement. Springer; 1st edition. ISBN-10: 3030242420. Editors: Charles Riviere, Pascal-Andre-Vedittoli

Aug 2019: **Classification of Combined Partial Knee Arthroplasty**. Garner, A. van Arkel. R. Cobb, J. The Bone and Joint Journal. 2019 Aug;101-B(8):922-928. doi: 10.1302/0301-620X.101B8.BJJ-2019-0125.R1.

9.3 Travelling Fellowships

Jan/Feb 2020: British Orthopaedic Research Society / Bone and Joint Research Journal Travelling Fellowship:

- University of Philadelphia - Prof Steve Kurtz
- Hospital for Specialist Surgery, New York - Dr Tim Knight, Dr Hollis Potter
- Columbia University, New York - Dr Nadeen Chahine
- Cornell University, Ithaca - Prof Marjolein van der Muelen
- University of Ottawa, Canada - Dr Paul Beaule
- Sunnybrook Research Institute, Toronto - Dr Albert Yee
- Western University, London (Ontario) - Dr David Holdsworth
- Orthopaedic Research Society Annual Meeting (Phoenix, Arizona)
- University of Denver - Prof Paul Rullkoetter

Sept/Oct 2019: European Society of Sports Traumatology, Knee Surgery and Arthroscopy (ESSKA) European Knee Arthroplasty Travelling Fellowship 2019:

- Metropolitan General Hospital, Athens, Greece - Dr Nikolaos Roidis
- Istituto Clinico Sant'Ambrogio – IRCCS Galeazzi, Italy - Dr Bruno Violante
- Medical University Innsbruck, Austria – Prof. Michael Liebensteiner
- Sonnenhof / Inselspital University Klinik, Bern, Switzeland - Dr Philipp Henle, Dr Frank Klenke
- Vulpius Klinik, Bad Rappenau, Germany – Prof. Michael Clarius
- Harmoniestaat, Antwerp, Belgium, Prof. Peter Verdonk
- ESSKA Speciality Days 2019 Madrid, Spain

Oct 2018: Royal College of Surgeons of England Stefan and Anna Galeski Travelling Fellowship, Cairo, Egypt: 11 days teaching basic surgical skills

- Ain Shams University Medical School
- Helwan University Medical School

9.4 National and International Podium Presentations

Sept 2021: **Biomechanics of the Lateral Compartment:** Garner, A. Bristol-Oxford Knee Groups (BOKG) Uni Knee Meeting, Bristol, UK. Invited faculty speaker.

May 2021: **Medial Bicompartmental Arthroplasty As An Alternative To Total Knee Arthroplasty in the Treatment of Severe Patellofemoral and Medial Compartment Arthritis.** Garner, A. Dandridge, O. Amis, A. van Arkel, R. Cobb, J. British Association of Surgery of the Knee Annual Conference. 'Best Free Paper' Prize

April 2021: **Medial Unicompartmental and Bicompartmental Arthroplasty are associated with Nearer-Normal Gait, Higher Patient Satisfaction and more Efficient Biomechanics than Cruciate-Retaining Total Knee Arthroplasty.** Garner, A. Cobb, J. World Arthroplasty Congress Virtual Meeting.

Dec 2020: **Combined Partial Knee Arthroplasty – A Viable Alternative to Total Knee Arthroplasty**. Garner, A. Institution of Mechanical Engineering Webinar Series: What's next for orthopaedic engineering. Invited keynote speaker

Nov 2020: **Extensor Function Following Partial, Combined Partial and Total Knee Arthroplasty Compared to the Native Knee.** Garner, A. Dandridge, O. Amis, A.A. Cobb, J. van Arkel R. International Society for Technology in Arthroplasty New Early-career Webinar Series

Nov 2020: **Improved Measurement of the Patellar Tendon Moment Arm: Implications for the Evaluation and Development of Knee Arthroplasty.** Dandridge, O. Garner, A. Amis, A.A. Cobb, J. van Arkel R. International Society for Technology in Arthroplasty New Early-career Webinar Series

Sept 2020: **Variation in the Patellar Tendon Moment Arm identified with an Improved Measurement Framework.** Dandridge, O. Garner, A. Amis, A. Cobb, J. van Arkel, R. British Orthopaedic Research Society

Feb 2020: **The Gait and Biomechanics of Bi-Unicondylar Arthroplasty.** Garner, A. Dandridge, O, Amis, A, van Arkel R. Cobb, J Orthopaedic Research Society Annual Meeting, Phoenix, USA

Oct 2019: **Bi-Unicondylar Arthroplasty: Near Normal Gait and Greater Extensor Mechanism Efficiency Compared to Total Knee Arthroplasty**. Garner, A. Dandridge, O. Amis, A. van Arkel, R. Cobb, J. International Society for Technology in Arthroplasty 32nd Annual Congress, Toronto, Canada.

Sept 2019: **Medial Bicompartmental Arthroplasty Retains the High functioning Gait Characteristics of Medial Unicompartmental Arthroplasty for Multi-compartment Gonarthrosis.** Garner, A. Lambkin, R. van Arkel. R. Cobb, J. British Orthopaedic Association Annual Congress, Liverpool. UK.

Sept 2019: **Addition of Partial Knee Arthroplasty to Newly Degenerate Native Compartments Retains a Functionally Superior Gait compared to Primary Total Knee Arthroplasty.** Garner, A. Lambkin, R. van Arkel. R. Cobb, J. British Orthopaedic Association Annual Congress, Liverpool. UK.

Sept 2019: **Bi-Unicondylar Arthroplasty preserves healthy gait characteristics and near-normal extensor mechanism efficiency compared to Total Knee Arthroplasty.** Garner, A. Dandridge, O. Amis, A. van Arkel, R. Cobb, J. 5th Joint British Orthopaedic Research Society and Bone Research Society Meeting, Cardiff, UK. "New Investigator Award"

Sept 2019: **Bi-Unicondylar Arthroplasty preserves the Anterior Cruciate Ligament, retaining near-normal anteroposterior stability in the treatment of medial and lateral tibiofemoral arthrosis**. Garner, A. Dandridge, O. Amis, A. van Arkel, R. Cobb, J. 5th Joint British Orthopaedic Research Society and Bone Research Society Meeting, Cardiff, UK.

May 2019: **Medial Bi-Compartmental Arthroplasty retains the Anterior Cruciate Ligament Resulting in a Higher Functioning Gait compared to Total Knee Arthroplasty.** Garner, A. Lambkin, R. van Arkel, R. Cobb, J. European Knee Society Arthroplasty Conference, Valencia, Spain. "Best Free paper" award

May 2019: **Bi-Unicondylar Arthroplasty Restores Healthy Gait Characteristics with Higher Function than Total Knee Arthroplasty.** Garner, A. Lambkin, R. van Arkel, R. Cobb, J. European Knee Society Arthroplasty Conference, Valencia, Spain. "Best Free Paper" Prize

March 2019: **Medial Bicompartmental Arthroplasty Retains the Functional Advantages of Medial Unicompartmental Arthroplasty with a Higher Functioning Gait Compared to Total Knee Arthroplasty.** Garner, A. Lambkin, R. van Arkel, R. Cobb, J. British Association of Surgery of the Knee (BASK) Annual Conference. Brighton, UK "Best free paper" Prize

Dec 2018: **Combined Partial Knee Arthroplasty is associated with more normal Gait and Higher Patient Satisfaction than Total Knee Arthroplasty.** Garner, A. Cobb, J. The Institution of Mechanical Engineers 'Engineering of the Knee' (IMechE – Knee) London. "Highest rated early career researcher" award

Oct 2018: **Second Surgery Following Partial Knee Replacement if Functionally Superior with Higher Patient Satisfaction than Primary Total Knee Replacement.** Garner, A. Lambkin, R. Cobb, J. International Society for Technology in Arthroplasty. London

Oct 2018: **The Outcome of 'Failed' Unicompartmental Knee Arthroplasty Surgery.** Garner, A. Cobb, J. The London Knee Meeting

May 2018: **The Outcome of Second Surgery Following Partial Knee Arthroplasty** Garner, A. Keane, B. Lambkin, R. Cobb, J. European Federation of National Associations of Orthopaedics and Traumatology 19th Annual Congress, Barcelona, Spain.

April 2018: **Revision Partial Knee Replacement: Superior Function and Satisfaction Compared to Primary Total Knee Replacement**. Garner, A. Lambkin, R. Keane, B. Cobb, J. The 2nd World Arthroplasty Congress. Rome, Italy.

Jan 2018: **Combined Partial Knee Replacement – a functionally superior alternative to Total Knee Replacement in Terms of Gait and Patient Reported Outcome Measures.** Garner, A. Lambkin, R. Keane, B. Cobb, J. The Partial Knee Meeting, Bruges, Belgium.

Oct 2017: **Strategies for Failed UKR: Should Revision Knee Replacement Always Be Considered As Failure of Primary Surgery? UKA: the outcome of 100 revisions**. In part based on Garner, A. Keane, B. Lambkin, R. Cobb, J. The London Knee Meeting.

10 Future Work and Conclusions

10.1 Patient Safety

There is good evidence that PKA is safer than TKA[174] but there is little evidence regarding the safety of CPKA. Primary CPKA is a significantly larger undertaking than PKA, with more soft-tissue dissection, additional bone resection and longer surgical times, compared to single compartment PKA. It is possible that this may negate the safety benefits of PKA, but there is little data on this. In the staged setting, it is clear that retention of a well-fixed primary PKA and the addition of a second PKA to a native compartment is a smaller "physiological insult" compared to revision to TKA, which may require extensive soft-tissue exposure; metaphyseal augments or stems. The concept of a 'second primary' gives optimism that staged CPKA may preserve the safety profile of primary PKA, but more data is required, to say this with any authority.

10.2 Survivorship

There is much work still to be done to determine whether CPKA is an appropriate alternative to TKA in the treatment of multi-compartment OA. Survivorship is not a stand-alone metric of success, however, it is a useful tool to quantify revision rates. Little is currently known of revision rates following compartmental arthroplasty. The fledgling data from the NJR suggests, perhaps predictably, that survivorship of compartmental arthroplasty is on a par with PFA, 4.5 times higher than TKA[76]. Given that the differentiation between medial and lateral UKA has only recently been made on the NJR, it is unlikely in the near future, that registry data will reliably indicate whether one CPKA configuration has a better or worse survivorship relative to another, or the impact of primary Vs. staged CPKA. Surgeons continue to be judged on revision rates of their primary procedures. Therefore, poor survivorship will, undoubtedly, be a barrier to wide-spread adoption, even amongst surgeons with a specialist PKA practise. Much further work needs to be done in this regard, including refinement of registry data, to better understand the outcomes of CPKA for patients.

10.3 Big Data

To date, there have been no multicentre cohort studies nor randomised control trials to compare primary CPKA to TKA (or indeed to PKA in isolation). Such data would prove very useful to compare

outcomes, but multiple limbs would be required to compare each subgroup based on pattern of disease, and to compare staged PKA to revision to TKA. To adequately power such a study would be a significant undertaking. In lieu of this, propensity matched studies of observational data may support surgeons in their decision making. Treatment of patellofemoral arthrosis continues to be controversial, therefore, the question remains as to whether all patients who may be considered suitable for BCA may in fact have equally good outcomes if treated with a UKA alone. Exact indications for CPKA must be clarified as and when the utilisation of these procedures increases. Within this, it is unclear whether a dysfunctional ACL should be a reason for exclusion. It has been suggested that elderly individuals with increased generalised soft-tissue stiffness may benefit from a UKA regardless of ACL restraint to anterior tibial translation. This has not been investigated in CPKA but such a study would be interesting. If shown that good outcomes following CPKA are possible, despite ACL dysfunction, the number of potentially eligible patients would, in all likelihood, significantly increase.

10.4 Objective and Subjective Outcomes

The clinical studies in this thesis relied on basic metrics: vertical ground reaction forces; temporospatial measurements and a snap-shot of PROMs. More detailed motion analysis would be very helpful, including detailed kinematics during gait, but also during functional activities including sit-to-stand, stair climbing and squatting. Pre- and post-operative data would help indicate the change in function and PROMs as a consequence of surgery, and enable us to track outcomes over time. Use of additional PROMs such as the Forgotten Joint Score, the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) amongst others, may provide further insight into satisfaction and quality of life, as would repeated measures at specific post-operative time-points.

10.5 Implant positioning and the role of in silico research

The use of two or more individual implant systems within the same knee brings about significant challenges. Unlike monolithic devices, when implanting unlinked prostheses, the surgeon is faced with a substantial number of variables with regards to component positioning, soft-tissue balancing and limb alignment. In CPKA there is an added complexity of where to position the components relative to each other, for example, how close to position the tibial trays in a Bi-UKA without the risk of undermining the tibial eminence leading to ACL avulsion[9, 275], or in what axial rotation; what is the

optimum alignment, how big should the gap between the femoral UKA component and the PFA trochlear component be; is there an impact of the patella button running across the femoral component of the UKA; what impact do multiple components have on the underlying bone; should techniques or strategy change in the very small knee compared to the very large; what is the impact of a 'mix and match' approach to implant selection, manufacturer or bearing type? All of these questions are, as yet unanswered. Our strategy to date has been to implant each component as if it were a stand-alone device, but there is little evidence as to whether this is appropriate.

To answer these questions *in vitro* or *in vivo* would be time consuming, expensive and difficult, due to the sheer number of variables and the comparatively crude methods of data collection. Recent advances in computational biomechanics and Finite Element Analysis have enabled these experiments to be performed *in silico.* Virtual surgery may be performed on optimised bone and soft-tissue models, each time amending a particular variable according to the research question. Combined with the newly emerging technologies of artificial intelligence and machine learning, the capabilities of these systems to rapidly and succinctly provide insight into these dilemmas is seemingly endless.

10.6 The Role of Robotics

The ability to independently orientate each UKA to the native compartmental anatomy is a strength of CPKA. However, this freedom increases technical difficulty and opportunity for error, which may limit widespread adoption. Throughout this thesis, CPKA have been implanted with standard instrumentation: by an expert surgeon in vivo, and a skilled but not expert surgeon in vivo, but across the world surgeon training in PKA is limited, CPKA virtually non-existent. Robotic surgery in orthopaedics continues to advance and may prove pivotal in overcoming the technical demands and variability of CPKA surgery though the use of sophisticated 3-Dimensional pre-operative planning and deliverance of surgical accuracy. In Bi-UKA, for example, robotics may help optimize tibial component axial rotation to avoid undercutting the ACL and achieve balance, which is otherwise difficult with two separate bearings. A recent prospective randomized controlled trial demonstrated that with robotic-arm assistance, Bi-UKA can preserve normal knee kinematics and accurately restore native joint line obliquity, over-coming the technical demands of conventional instrumentation[309].The MAKO™ system (Stryker, Warsaw, Indiana USA) already supports and has the capability to assist compartmental arthroplasty, though it is unclear how many procedures have been undertaken to date.

10.7 Comparison with Single Compartment Partial Knee Replacement

The question remains as to whether it is necessary to replace the patellofemoral compartment at all, in the presence of medial or lateral tibiofemoral OA. If it transpires that there is no benefit in terms of the biomechanics, objective or subjective outcomes, it may seem unnecessary to subject the patient to primary bicompartmental disease, reserving these procedures for revision cases, where the PFJ subsequently becomes symptomatic, in the presence of a well-functioning UKA. Chapter 5 demonstrates that few significant differences were found between UKA and BCA, therefore whilst there is no biomechanical disadvantage of CPKA, there is no measurable biomechanical benefit either in comparison to UKA alone in disease-free specimens. The arguments in favour of CPKA Vs. single compartment PKA therefore fall to functional and patient reported clinical outcomes. BCA may be more suitable for those who predominantly complain of anterior knee symptoms, for example, in the presence of significant medial or lateral tibiofemoral OA. Future studies comparing the gait and PROMs between UKA and CPKA would be in very interesting to determine which patients truly benefit from CPKA, and which would be served better by a UKA alone, with the option of revision to a CPKA later if required.

11 Conclusions

This thesis has revisited the fundamental principles that Gunston, Charnley, Marmor, Goodfellow, O'Connor and others based their original work upon: targeting joint replacement to the pattern of wear, whilst preserving essential functional cruciate ligaments, peri-articular tissues and healthy bone. This time, however, the concepts are approached with the benefit of modern technologies, a wealth of research and published literature and a healthy dose of hindsight! TKA remains the standard treatment for multi-compartment osteoarthritis, benefiting millions of people across the world, but dissatisfaction rates of up to 25% do not appear to be reducing.

The basic principles of anatomy, physiology and biomechanics must prevail. The native knee is an extraordinary machine and no replica to date comes close to its complexity, precision or functional capabilities. It is the responsibility of the surgeon to treat pathology whilst, as far as is possible, simultaneously preserving healthy native tissue. To sacrifice a ligament of such importance as the ACL has significant implications for the patient and inevitably results in sub-optimal outcomes that, as yet, no design of TKA has been able to address. There are few other branches of medicine that so readily forgo a structure of such fundamental importance, only to substitute it with something inferior.

There is little that is truly novel in arthroplasty, and the concept of compartmental arthroplasty is by no means an exception. However, the simple principles of treatment targeted to the location of disease, whilst preserving all else, seems sensible, rational and entirely achievable. There is little that is experimental about CPKA: the implants are readily available, licensed and evidence-based; experienced PKA surgeons have the capabilities, skills and insight to undertake the procedures without delay and young surgeons have the enthusiasm to learn the science and art of joint-preserving arthroplasty, adopting contemporary techniques in the quest for improved outcomes.

The work presented here is intended to contribute to an ever-increasing evidence base, and to stimulate debate. These data are intended to support clinicians and their patients when contemplating compartmental alternatives to TKA where once their use may have been considered unsubstantiated. Compartmental arthroplasty is re-emerging, with new evidence to indicate its benefits and a renewed enthusiasm for its place in the armoury of treatments against debilitating osteoarthritis.

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13 Appendix

13.1 Courses

Mar 2018:	**Ensuring Integrity 1:**	Plagiarism Awareness Online Course
16th May 2018:	**Writing for Success 3:**	Literature Review
15th / 17th May 2018	**Statistics 3:**	Introduction to Statistics Using SPSS 1 & 2
5th June 2018	**Information Landscape:**	EndNote

March 2018 **Oxford Unicompartmental Knee Instructional Course.** University of Oxford

13.2 Funding

Year 1: Sir Michael Uren Foundation Clinical Research Fellowship' Salary and consumables **£160,000**

Years 2 & 3: 'Joint Dunhill Medical Trust and Royal College of Surgeons' Fellowship to fund salary costs for years two and three **£128,000**

13.3 Rebuilding the Extension Rig

The previous Extension rig had been used over many years but had developed a number of issues. First, the base of the rig was wooden, and repeated exposure to tissue and cleaning fluids had left it warped, rotten and contaminated. This was replaced with a single sheet of aluminium, stiffened by aluminium struts. The femur had previously been secured using a femoral intramedullary rod, held in the rig with a grub screw. However, this often resulted in rotation of the specimen and "sagging", requiring a femoral support to stabilise the knee (Figure 13.1). This was overcome by potting the specimen in cement and bolting the pot rigidly to the rig. The side panels which controlled the flexion angle were flexible (Figure 13.3) and unsuitable for the extension loads required, resulting in bending of the restraining bar and distortion of the reading. These were replaced with steel plates, fixed rigidly to the aluminium base using an adjustable frame supported by vertical struts. Finally, previous experiments had not specifically dissected out or tensioned the hamstring tendons, so additional pulleys were required at the back of the rig to accommodate these.

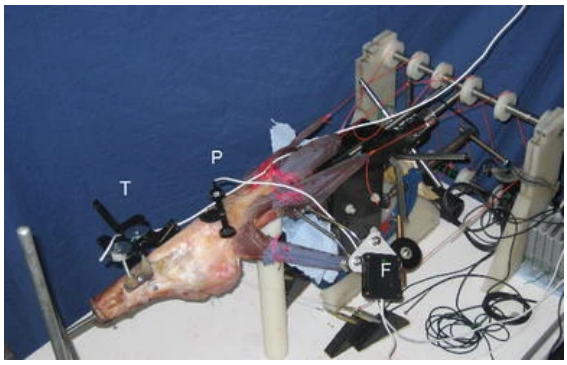


Figure 13.1. A previous iteration of the Extension Rig prior to reconfiguration

Reproduced under licence 5050850224750 from Ghosh et. al.[455]

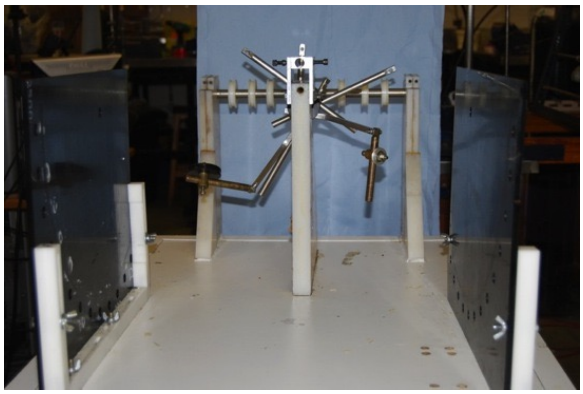


Figure 13.2. Front view of a previous iteration of the Extension Rig prior to reconfiguration

From Joseph 2015 [456]

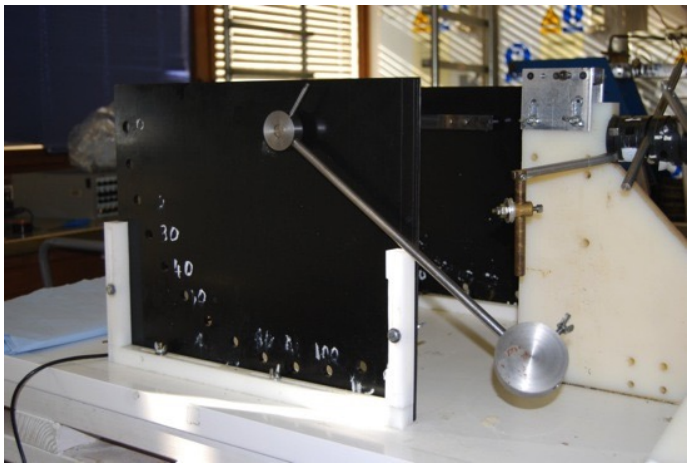


Figure 13.3. Rear side view of a previous iteration of the Extension Rig prior to reconfiguration

From Joseph 2015[456]

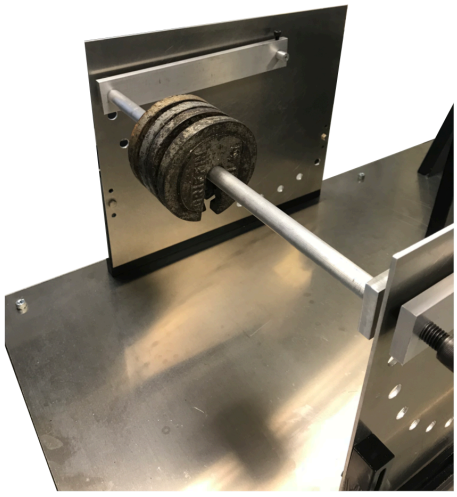


Figure 13.4. Calibration of the Extension Rig, here shown loaded with 4Kg.

The restraining bar were instrumented with a gauge that measured the strain in volts via a data logger. To convert this reading to force, the bar was loaded with weights of a known mass, the readings from which were plotted as volts against force. The readings were repeated five times and averaged in order to later convert the output readings into force measurements.

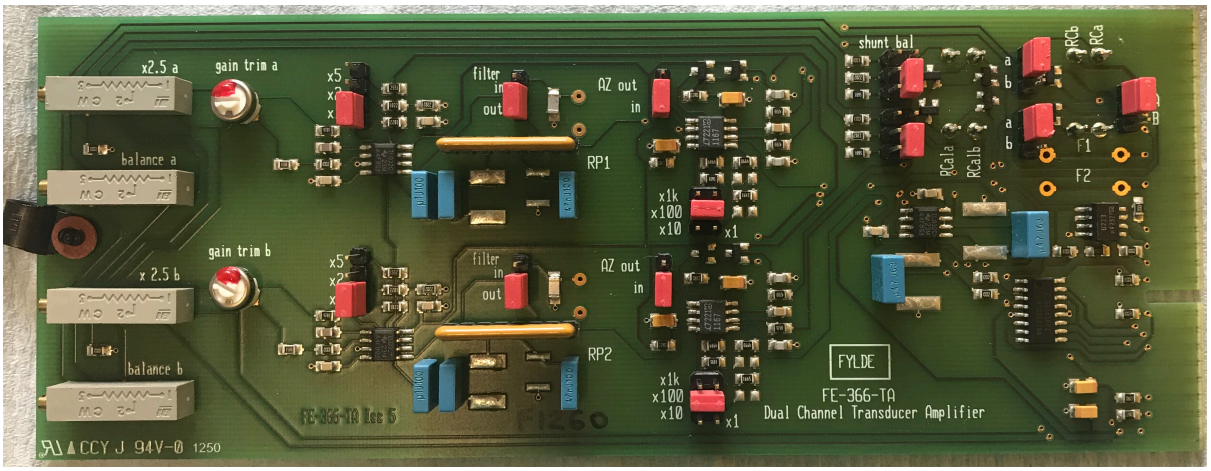


Figure 13.5. Circuit board configuration, data logger used in cadaveric studies, for future reference

13.4 Gait Studies Additional Data

	Subgroup	Primary Procedure	Implant	Manufacturer	Second Procedure	Implant	Manufacturer
1	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Domed Lateral	Zimmer Biomet
2	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Domed Lateral	Zimmer Biomet
3	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Domed Lateral	Zimmer Biomet
4	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Fixed Lateral	Zimmer Biomet
5	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Fixed Lateral	Zimmer Biomet
6	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Fixed Lateral	Zimmer Biomet
7	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Fixed Lateral	Zimmer Biomet
8	Bi-UKA	UKA-M	Oxford® Partial Knee	Zimmer Biomet	UKA-L	Oxford® Fixed Lateral	Zimmer Biomet
9	Bi-UKA	UKA-L	Oxford® Domed Lateral	Zimmer Biomet	UKA-M	Oxford® Partial Knee	Zimmer Biomet
10	Bi-UKA	UKA-L	Oxford® Domed Lateral	Zimmer Biomet	UKA-M	Oxford® Partial Knee	Zimmer Biomet
11	Bi-UKA	UKA-L	Oxford® Domed Lateral	Zimmer Biomet	UKA-M	Oxford® Partial Knee	Zimmer Biomet
12	Bi-UKA	UKA-L	Oxford® Domed Lateral	Zimmer Biomet	UKA-M	Oxford® Partial Knee	Zimmer Biomet
13	Bi-UKA	UKA-L	Oxford® Domed Lateral	Zimmer Biomet	UKA-M	Oxford® Partial Knee	Zimmer Biomet
14	Bi-UKA	UKA-L	JOURNEY™ UNI	Smith & Nephew	UKA-M	Oxford® Partial Knee	Zimmer Biomet
15	Bi-UKA	UKA-L	St Georg SLED	LINK®	UKA-M	St Georg SLED	LINK®
16	BCA-M	UKA-M	Oxford® Partial Knee	Zimmer Biomet	PFA	Gender Solutions®	Zimmer Biomet
17	BCA-M	UKA-M	Oxford® Partial Knee	Zimmer Biomet	PFA	JOURNEY™ PFJ	Smith & Nephew
18	BCA-M	UKA-M	Oxford® Partial Knee	Zimmer Biomet	PFA	Avon™	Stryker®
19	BCA-M	PFA	JOURNEY™ PFJ	Smith & Nephew	UKA-M	JOURNEY™ UNI	Smith & Nephew
20	BCA-M	PFA	KineMatch® PFR	Kinamed® incorporated	UKA-M	Oxford® Partial Knee	Zimmer Biomet
21	BCA-L	UKA-L	Oxford® Fixed Lateral	Zimmer Biomet	PFA	SIGMA® HP	DePuy Synthes
22	BCA-L	UKA-L	Oxford® Domed Lateral	Zimmer Biomet	PFA	P.F.C® SIGMA®	DePuy Synthes
23	BCA-L	UKA-L	Uniglide™	Corin	PFA	JOURNEY™ PFJ	Smith & Nephew

Table 13.1 Implant order and combinations by brand and manufacturer for subjects in gait study 6, staged combined partial knee arthroplasty.

Each line represents one subject. Reproduced open access with permission CC BY 4.0[442]

13.5 Paper Based PROMs Survey

The following paper-based Oxford Knee Score and EQ-5D 5L surveys and on line JointPro.co.uk surveys were used to gather data for Chapter 7

Oxford Knee Score Page 1

PROBLEMS WITH YOUR KNEE

During the past 4 weeks.. ✓tick one box for every question

1 *During the past 4 weeks.....* How would you describe the pain you usually have from your knee?

None ❑ | Very mild ❑ | Mild ❑ | Moderate ❑ | Severe ❑

2 *During the past 4 weeks.....* Have you had any trouble with washing and drying yourself (all over) because of your knee?

No trouble at all ❑ | Very little trouble ❑ | Moderate trouble ❑ | Extreme difficulty ❑ | Impossible to do ❑

3 *During the past 4 weeks.....* Have you had any trouble getting in and out of a car or using public transport because of your knee? (whichever you would tend to use)

No trouble at all ❑ | Very little trouble ❑ | Moderate trouble ❑ | Extreme difficulty ❑ | Impossible to do ❑

4 *During the past 4 weeks.....* For how long have you been able to walk before pain from your knee becomes **severe**? (*with or without a stick*)

No pain/ More than 30 minutes ❑ | 16 to 30 minutes ❑ | 5 to 15 minutes ❑ | Around the house only ❑ | Not at all - pain severe when walking ❑

5 *During the past 4 weeks.....* After a meal (sat at a table), how painful has it been for you to stand up from a chair because of your knee?

Not at all painful ❑ | Slightly painful ❑ | Moderately painful ❑ | Very painful ❑ | Unbearable ❑

6 *During the past 4 weeks.....* Have you been limping when walking, because of your knee?

Rarely/ never ❑ | Sometimes, or just at first ❑ | Often, not just at first ❑ | Most of the time ❑ | All of the time ❑

Oxford Knee Score© Department of Public Health, University of Oxford, Old Road Campus, Oxford OX3 7LF, UK. /P.T.O

Oxford Knee Score Page 2

During the past 4 weeks... ✓tick one box for every question

7 *During the past 4 weeks.....* **Could** you kneel down and get up again afterwards?

Yes, Easily ❑ | With little difficulty ❑ | With moderate difficulty ❑ | With extreme difficulty ❑ | No, Impossible ❑

8 *During the past 4 weeks.....* Have you been troubled by pain from your knee in bed at night?

No nights ❑ | Only 1 or 2 nights ❑ | Some nights ❑ | Most nights ❑ | Every night ❑

9 *During the past 4 weeks.....* How much has pain from your knee interfered with your usual work *(including housework)*?

Not at all ❑ | A little bit ❑ | Moderately ❑ | Greatly ❑ | Totally ❑

10 *During the past 4 weeks.....* Have you felt that your knee might suddenly 'give way' or let you down?

Rarely/ never ❑ | Sometimes, or just at first ❑ | Often, not just at first ❑ | Most of the time ❑ | All of the time ❑

11 *During the past 4 weeks.....* **Could** you do the household shopping on your own?

Yes, Easily ❑ | With little difficulty ❑ | With moderate difficulty ❑ | With extreme difficulty ❑ | No, Impossible ❑

12 *During the past 4 weeks.....* **Could** you walk down one flight of stairs?

Yes, Easily ❑ | With little difficulty ❑ | With moderate difficulty ❑ | With extreme difficulty ❑ | No, Impossible ❑

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EuroQoL 5D 5 Level

Under each heading, please tick the ONE box that best describes your health TODAY

MOBILITY
- I have no problems in walking about ❑
- I have slight problems in walking about ❑
- I have moderate problems in walking about ❑
- I have severe problems in walking about ❑
- I am unable to walk about ❑

SELF-CARE
- I have no problems washing or dressing myself ❑
- I have slight problems washing or dressing myself ❑
- I have moderate problems washing or dressing myself ❑
- I have severe problems washing or dressing myself ❑
- I am unable to wash or dress myself ❑

USUAL ACTIVITIES *(e.g. work, study, housework, family or leisure activities)*
- I have no problems doing my usual activities ❑
- I have slight problems doing my usual activities ❑
- I have moderate problems doing my usual activities ❑
- I have severe problems doing my usual activities ❑
- I am unable to do my usual activities ❑

PAIN / DISCOMFORT
- I have no pain or discomfort ❑
- I have slight pain or discomfort ❑
- I have moderate pain or discomfort ❑
- I have severe pain or discomfort ❑
- I have extreme pain or discomfort ❑

ANXIETY / DEPRESSION
- I am not anxious or depressed ❑
- I am slightly anxious or depressed ❑
- I am moderately anxious or depressed ❑
- I am severely anxious or depressed ❑
- I am extremely anxious or depressed ❑

Figure 13.6. Paper based Oxford Knee Scores and EuroQoL 5D 5 Level Index used for some patients in Chapter 7

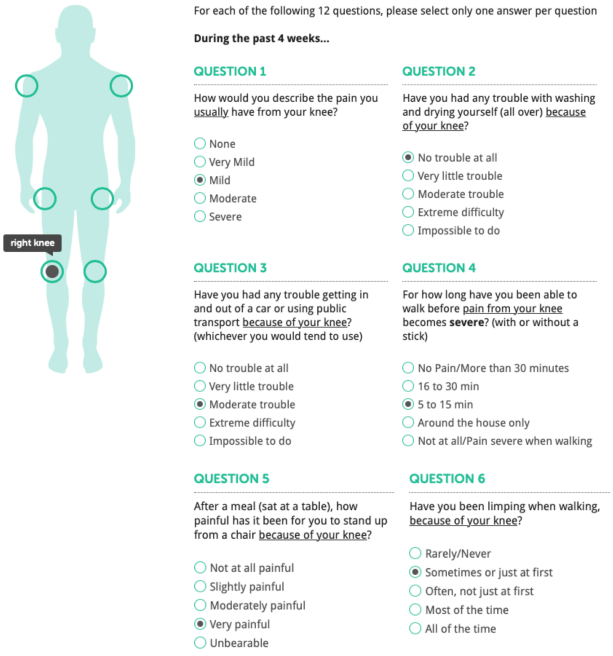


Figure 13.7. Oxford Knee Score Questions 1-6 completed via JoinrPRO regarding right knee

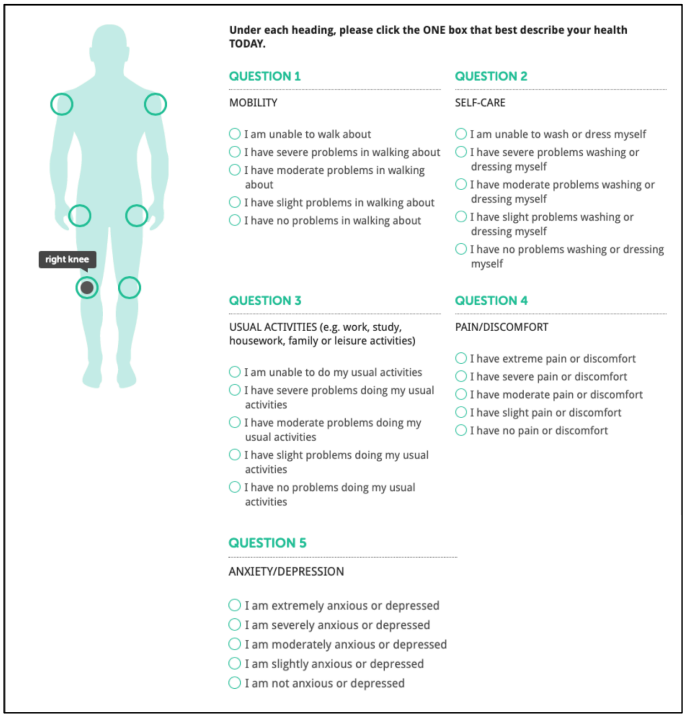
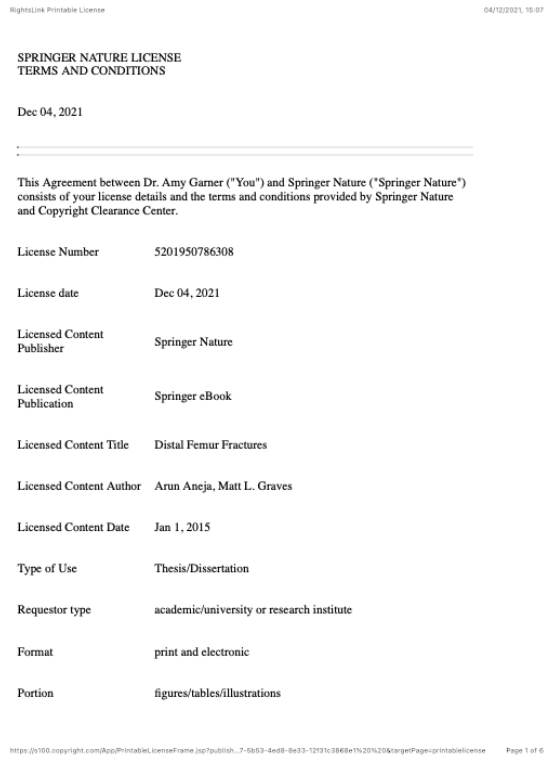


Figure 13.8. EQ-5D 5 Level score completed via JointPRO regarding the right knee

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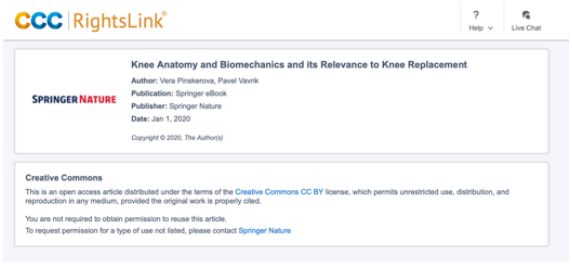
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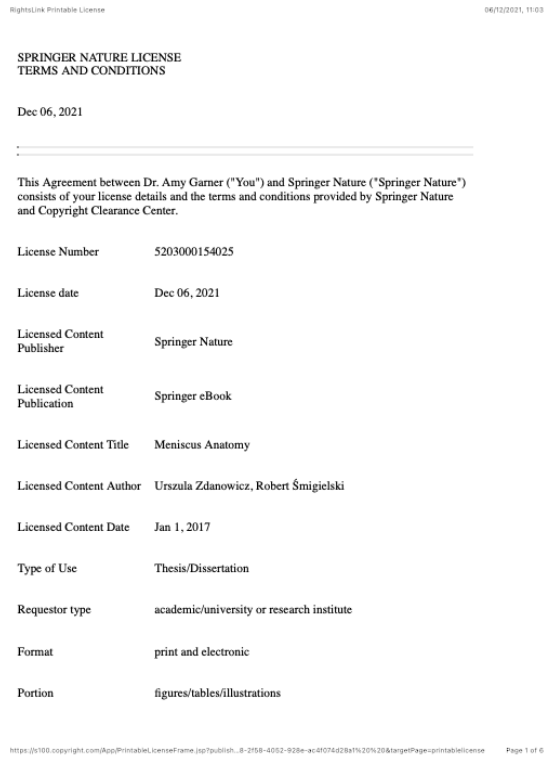
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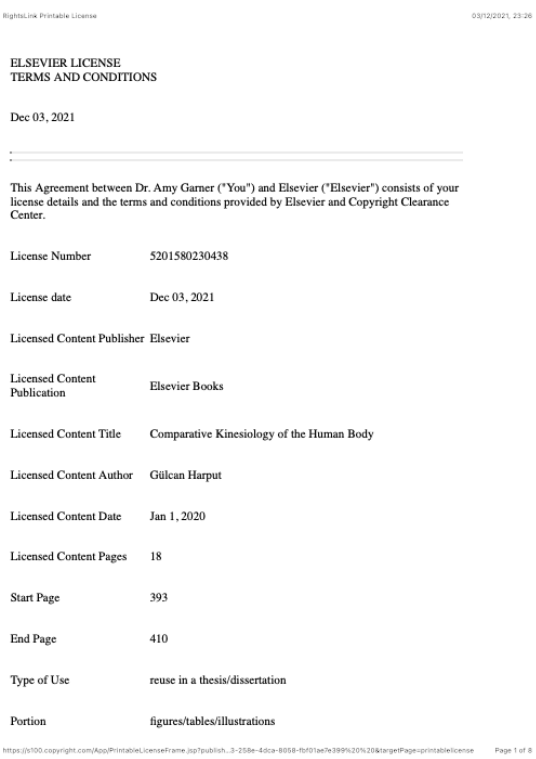
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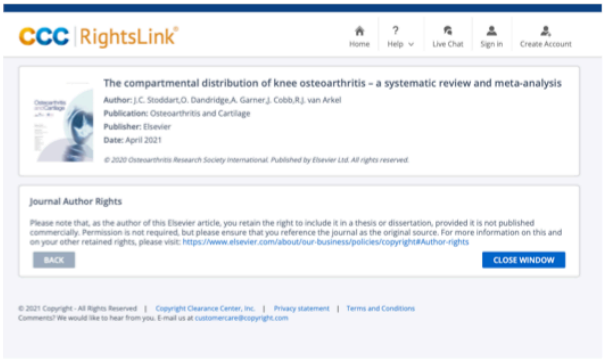
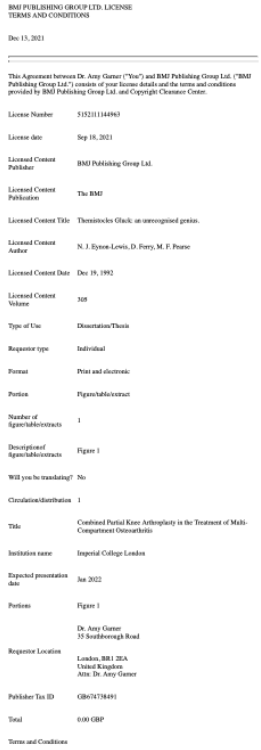


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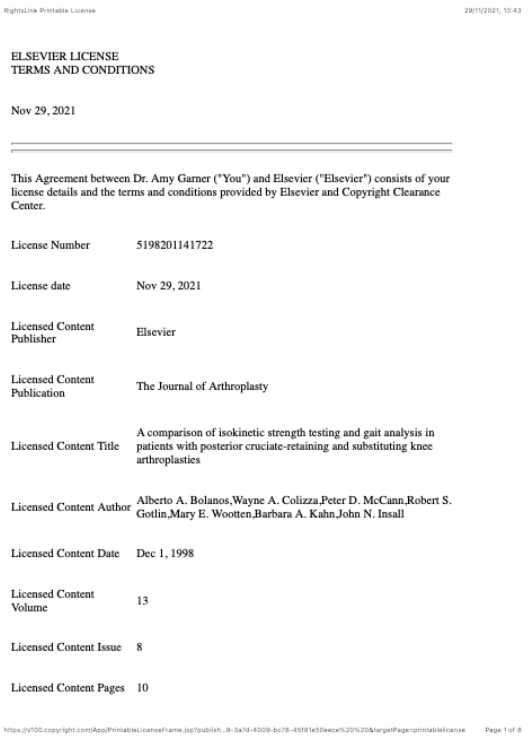
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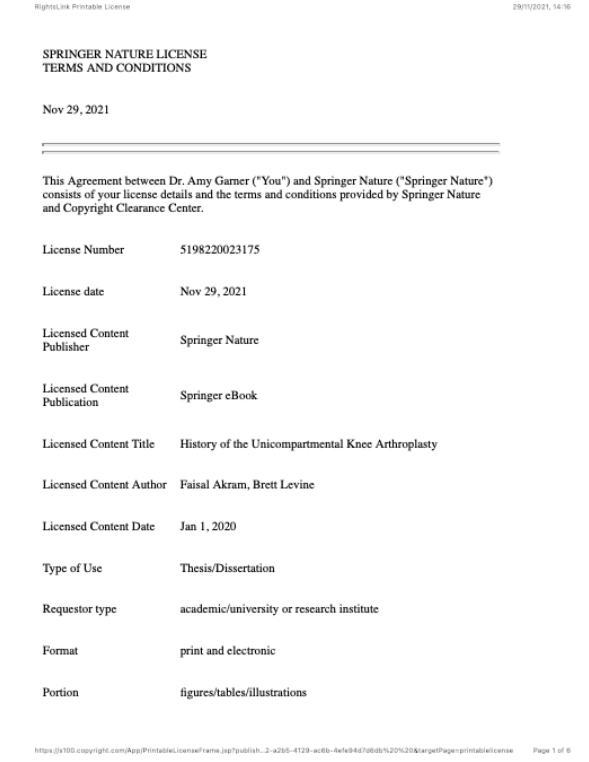
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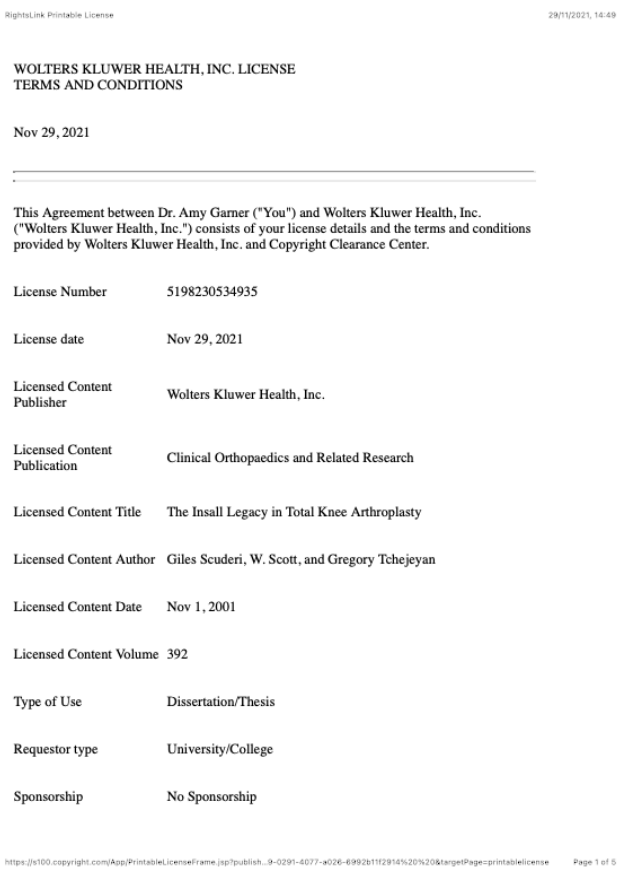
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Partial and Combined Partial Knee Arthroplasty: Greater Anterior-Posterior Stability Than Posterior Cruciate–Retaining Total Knee Arthroplasty

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- J. P. Cobb: Conceptualized the study, Reviewed the data, Reviewed, edited, and revised the manuscript.
- R. J. van Arkel: Conceptualized and designed the study, Analyzed the data, Wrote, reviewed, edited, and revised the manuscript.

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Validity of repeated-measures analyses of in vitro arthroplasty kinematics and kinetics

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Chapter 6 & Chapter 7

Knee Surgery, Sports Traumatology, Arthroscopy
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KNEE

Medial bicompartmental arthroplasty patients display more normal gait and improved satisfaction, compared to matched total knee arthroplasty patients

Amy J. Garner[1,2,3,4] · Oliver W. Dandridge[2] · Richard J. van Arkel[2] · Justin P. Cobb[1]

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KNEE

The compartmental approach to revision of partial knee arthroplasty results in nearer-normal gait and improved patient reported outcomes compared to total knee arthroplasty

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Appendix