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**The Patellofemoral Joint. Incongruence, Instability and Arthritis**

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The Patellofemoral Joint.  
Incongruence, Instability and Arthritis.



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## Abstract

The relationship between patellofemoral joint (PFJ) instability and arthritis is little explored. The PFJ cartilage transmits more force per area than any other joint cartilage. The unstable joint may have a different pattern of congruence to the stable joint.

A case-controlled study without matching was performed, amongst the co-variables included were demographic and anatomic risk factors for patellofemoral instability. In the final analysis, there were 73 patients in the patellofemoral arthritis arm and 87 patients in the medial unicompartmental arthritis arm. The co-variables of female sex, patella alta and early onset of symptoms increased the odds of developing patellofemoral arthritis over medial compartmental arthritis.

The results of the first study stimulated a second study. This study sought to characterise the congruence of the patellofemoral joint during activity, to better understand if the surface area available for force transmission differed in cases of instability. An imaging study of eighteen patients with a history of PFJ instability was performed, this study evaluated the congruence of the PFJ throughout flexion. The study found that the unstable PFJ is less congruent than the normal PFJ throughout knee range. Stabilising the joint (by various surgical procedures) had the unintended consequence of restoring joint congruence.

In the final study a dynamic evaluation of 13 ambulant patient was performed. The gait of people with patellar instability and those with normal knees were compared by inverse dynamics analysis. Comparison included kinematic, morphometric and force data in a linked-segment model and is used to evaluate limb joint angular excursions, net joint moments and net joint powers. The gait cycle of some of the patellar instability patients was characterised by quadriceps inhibition gait where the patient failed to generate an extensor moment during weight-bearing. In eight of the patients the preoperative data was compared to data collected one year after surgery. Restoration of normal gait was noted.

An association between instability and arthritis is supported by these studies. The precise pathway between instability and arthritis remains unknown. Patients with PFJ instability experience dislocations that may cause cartilage damage. They also have abnormal joint anatomy, biomechanics and gait. In addition to traumatic dislocations; excessive loading of cartilage due to abnormalities of joint anatomy and incongruence may lead to accumulated damage and arthritis.

I declare that the work in this dissertation was carried out in accordance with the requirements of the University's *Regulations and Code of Practice for Research Degree Programmes* and that it has not been submitted for any other academic award. Except where indicated by specific reference in the text, the work is the candidate's own work. Work done in collaboration with, or with the assistance of, others, is indicated as such. Any views expressed in the dissertation are those of the author.

SIGNED: ..... DATE:.....



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Work completed by myself for studies:

Literature review (All)

Study design (All)

Apparatus design (study 2)

Application to ethics (All)

Data collection for studies (All with exception of database data in study 1)

Statistical analysis (All- with advice from statistician).

Writing of thesis (All)

Writing and other preparations of manuscript for publications arising from this work (all)

Work completed by others:

Database element in study 1 was pre-existing.

Sending postal questionnaire for study 1 (support from research assistant with)

Imputation of data from by postal questionnaire for study 1 (support from research assistant)

Operation of magnetic resonance imaging machine (hospital radiographers)

Calculation of vectors (study 3)

Assistance with writing of manuscript for publications arising (study 1)

Assistance with writing of manuscript for publications arising (study 2)

## Abbreviations:

ABC	Ageing and body composition
ACL	Anterior cruciate ligament
ANOVA	Analysis of Variance
Fy	Antero-posterior to direction of travel
ALSPAC	Avon Longitudinal Study of Parents and Children
BMI	Body mass index
BOKS	Boston Osteoarthritis of the Knee Study
CI	Confidence Interval
CLSI	Clinical and laboratory Standards institute
CT	Computed tomography
DDH	developmental dysplasia of the hip
ELSA	English Longitudinal Study of Ageing
EXP	Exponential
EXP(B)	Exponentiation of the B co-efficient (Odds ratio)
GE	General Electric
GRF	ground reaction forces
ISR	Insall-Salvati ratio
IRAS	Integrated Research Application System
IKDC	International Knee Documentation Committee
IQR	Inter-quartile Range
K1	Maximum +ve knee moment
K2	Maximum -ve knee moment
LP	length of the patella
LT	length of the patella tendon
MRI	magnetic resonance imaging
MD	Mean difference
MPFL	Medial patellofemoral ligament
Fx	Medio-lateral to direction of travel
MOST	Multicentre Osteoarthritis Study
MSV	Milli-severts
NHS	National Health Service
NY	New York
OA	Osteoarthritis
P	Probability
P1	Mild gait pathology group
P2	Severe gait pathology group
PFPS	patellofemoral pain syndrome
PFJ	Patellofemoral Joint
PACS	picture archiving and communication system
Q-angle	Quadriceps angle
RA	Rheumatoid arthritis

SD	Standard Deviation
Sig.	Significance
SLE	Systemic Lupus Erythematosus
SPSS	Statistical Package for the Social Sciences
TTTG	tibial tuberosity to trochlea groove
TSM	Total Support Moment
USA	United States of America
VIF	variance inflation factor test
VMO	vastus medialis oblique
Fz	Vertical to direction of travel
WOMAC	Western Ontario and McMaster Universities Arthritis Index

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**Ethics:** Ethical approval was sought via the Integrated Research Application System (IRAS). Approval was sought and attained on 7th of June 2012. The Southwest research ethics council granted approval number 12/SW/0155. Prospective ethical approval from the local research ethical committee has been previously attained to cover observational studies data from the Bristol Knee Database.

## Chapter 1a: Symptomatic osteoarthritis of the patellofemoral joint and patellar instability

### Knee arthritis an Introduction:

Osteoarthritis (OA) is the most common joint disease in the developed world. Symptomatic knee OA occurs in 10% of men and 13% of women aged 60 years or older. The prevalence of symptomatic OA is likely to increase due to growth of an ageing population and the increased prevalence of obesity. The entire knee may be affected, alternatively the medial part, the lateral part or the anterior part (patellofemoral compartment). The compartments may be affected in isolation or in any combination.

“Disease localization is a mysterious business. Why does eczema affect one part of your skin and psoriasis another? And why does RA spare the distal interphalangeal joints, the site most likely to be attacked by OA?... Just as SLE and scleroderma share similar hereditary disposition, autoantibodies and inflammation, so do all forms of osteoarthritic disease... medial OA of the knee and patellofemoral OA of the knee become distinct entities, as worth of distinction from each other as SLE and scleroderma.” (Dieppe and Kirwan, 1994)

### Osteoarthritis of the knee

The aetiology of OA is multi-factorial and it may be considered the result of an interplay between systemic and local factors. The 2014 “Atlas of Osteoarthritis” defines osteoarthritis as “a group of overlapping disorders with different aetiologies but similar biologic, morphologic and clinical outcomes . The disease processes affects articular cartilage, subchondral bone, synovium, capsule and ligaments. Ultimately, cartilage degenerates with fibrillation, fissures, ulceration and full thickness loss of joint surface.” (Arden et al).

The severity of osteoarthritis may be classified by numerous systems, the most widely used is the 1957 Kellgren and Lawrence radiological technique. The Kellgren and Lawrence classification defines the severity of the arthritis on the antero-posterior knee radiograph:

- Grade 1: Doubtful joint space narrowing and possible osteophytic lipping.
- Grade 2: Definite osteophytes and possible joint space narrowing.
- Grade 3: Moderate multiple osteophytes, definite joint space narrowing, some sclerosis, possible bone end deformity.
- Grade 4: Large osteophytes, marked joint space narrowing, severe sclerosis definite deformity of bone ends.

## Radiological vs clinical

Radiographs are typically used to characterize the structural changes associated with arthritis and aid in diagnosis. Radiographs are typically used in the initial diagnosis of arthritis. They have also been used to estimate prognosis, guiding surgical treatment, evaluating disease progression and the results of therapies (Bedson and Croft, 2008). Several authors have attempted to evaluate the concordance of a radiologic diagnosis of arthritis and knee pain in the general population. These findings are summarised in tables 1&2, each of these studies focuses on Kellgren & Lawrence grade 2. Whether we consider the presence of radiologically diagnosed arthritis in knee pain or knee pain in radiologically identified arthritis the association is weak. Only in one study does it exceed 50%. This is a significant consideration that a surgeon must take into consideration when counselling patients regarding the suitability for invasive therapies such as arthroplasty.

Study	Age range	Proportion with radiological arthritis
(Lachance et al, 2001)	40-53	15
(Hart et al, 1991)	45-65	19
(Claessens et al, 1990)	> 45	36
(Odding et al, 1998)	> 55	39
(McAlindon et al, 1992a)	> 55	76
(Brandt et al, 2000)	> 65	49
(Lethbridge-Cejku et al, 1995)	19-92	53
(Williams et al, 2004)	51-80	43

**Table 1. Proportion of patients with knee pain who also have a radiologically identified Kellgren-Lawrence grade 2+ osteoarthritis.**

Study	Age range	Proportion with knee pain. (KL2+)	Proportion with knee pain. KL2	Proportion with knee pain. (KL3+)_
(Lachance et al, 2001)	40-53	35	-	-
(Hart et al, 1991)	45-65	56	-	-
(Davis et al, 1992)	45-75	-	41	59
(Claessens et al, 1990)	>45	24	-	-
(Odding et al, 1998)	>55	-	30	59
(Felson et al, 1997)	>63	40	-	-
(Lethbridge-Cejku et al, 1995)	19-92	-	30	64

**Table 2. Proportion of patients with radiologically confirmed Kellgren-Lawrence grade 2+ osteoarthritis who also have knee pain.**

There are several explanation for this poor association, these studies represent a variety of methodologies. They assess the presence of radiological arthritis and pain in different ways.



and focus on the AP radiograph. Other radiological views such as lateral, skyline or Rosenberg view can increase reporting of arthritis in the pain group (Williams et al, 2004). Indeed some authors have directly correlated an increase in the number of radiographic views with the radiological diagnosis of arthritis (Peat et al, 2007). Increasing severity of arthritis does however increase the presence of knee pain. Some of the studies mentioned above included an assessment of KL3+ arthritis and in those studies the association is closer.

Possibly a greater challenge for these authors was the assessment of pain. The experience of pain is bound up with stiffness, disability, previous experience, individual personality and environmental factors amongst others. In a systematic review Bedson et al concluded that pain was an imprecise marker of arthritis even older patients (Bedson and Croft, 2008).

### **Prevalence and incidence**

The prevalence of knee arthritis and symptomatic knee arthritis is variably reported. Variation may exist in the population prevalence between geographical and demographic boundaries.

The English Longitudinal Study of Ageing (ELSA) reports on 1693 workers over the age of 50. Three hundred and eight were lost at the 4-year follow-up. ELSA found that 18.2% of that population studied have symptomatic knee arthritis and 6.1% severe (defined as having undergone arthroplasty, severe pain most of the time or unable to walk >1/4 mile) symptomatic knee arthritis. 4.11 million people in the UK are currently thought to have arthritis of the knee.

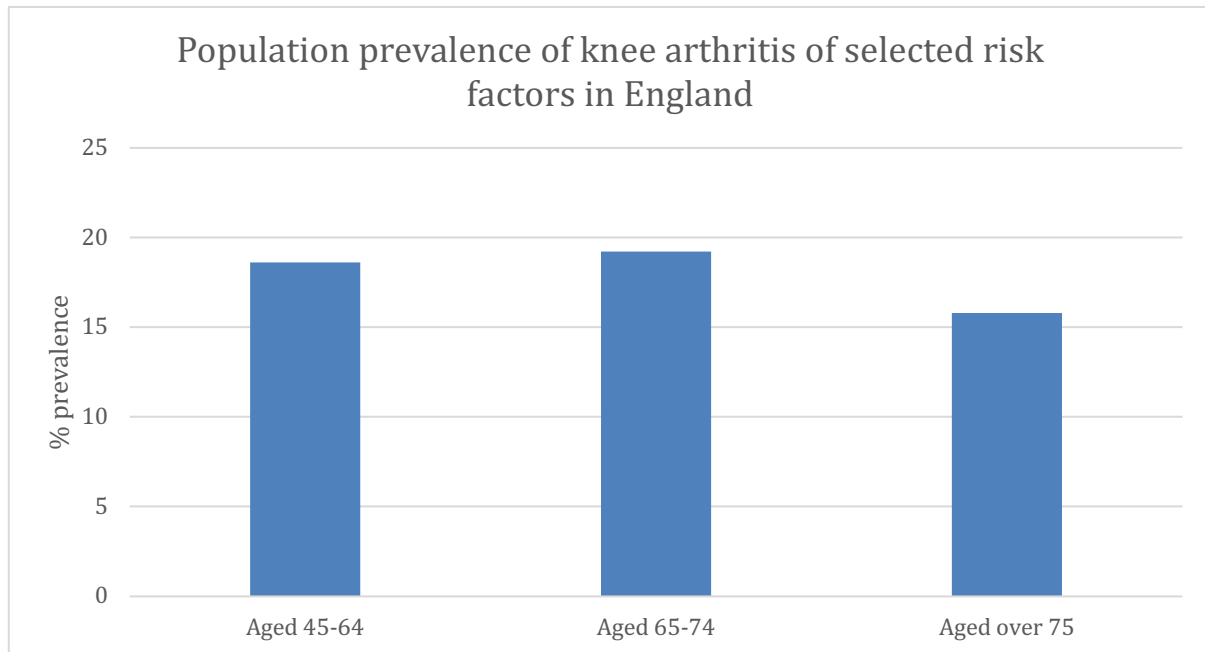
The Framingham study in the United States had similar findings with the prevalence of radiographic knee osteoarthritis being 19.2% amongst those over 45 years of age. In contrast, however, the Johnston County Osteoarthritis Project found the prevalence of radiographic knee osteoarthritis in this age group to be 27.8%, the National Health and Nutrition Examination Survey III found it to be 37% amongst those over 60 (Lawrence et al, 2008).

### **Risk factors for arthritis of the knee**

Increasing age, female sex, increased body mass, previous knee trauma, and joint laxity have all played roles in the development of osteoarthritis of the lower limb.

Age is probably the strongest risk factor for osteoarthritis. Inhabitants of a Dutch village were assessed for the prevalence of osteoarthritis in multiple joints. The investigators found that radiologically confirmed osteoarthritis is strongly linked to age in all joints (van Saase et al, 1989). Van Saase reported the incidence rising steeply with age after 50 years, although in 1995 Oliveira noted that this tails off after 80 years. This may be due to the increasing sedentary

activities of elderly people and then the competing risk associated with higher rates of mortality in that group. These findings appear to reflect our view of the UK population as seen through the UK ELSA study. Advancing age is a risk factor for arthritis and the converse is also true, arthritis has been demonstrated to be a risk factor for early mortality (Nuesch et al, 2011).

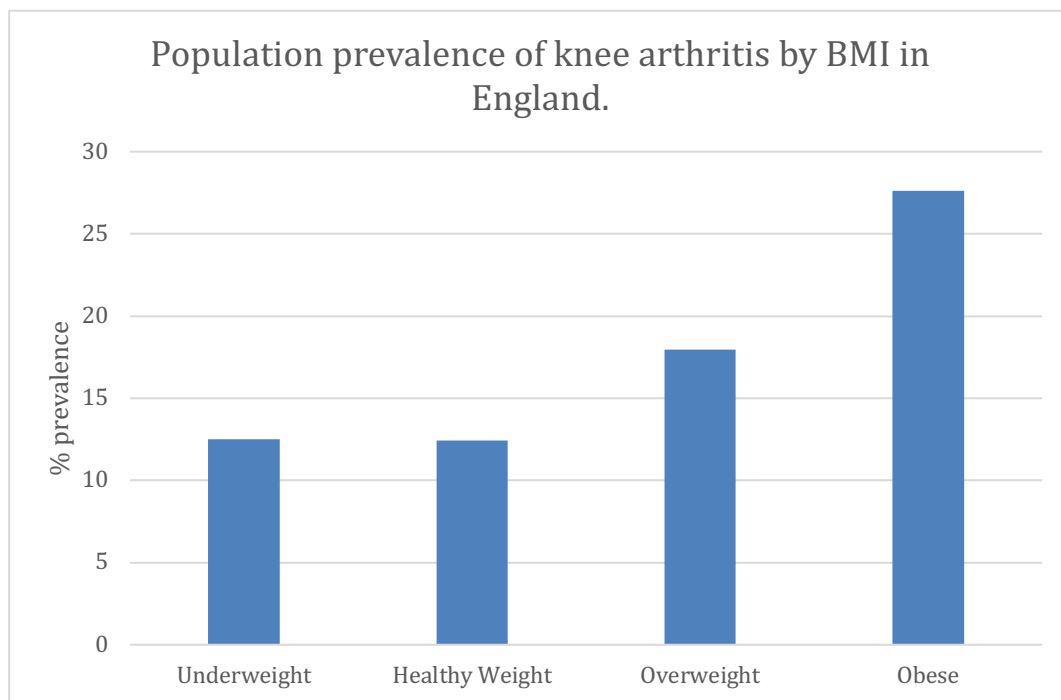


**Figure 1. Prevalence of knee osteoarthritis by age from Arthritisresearchuk.org**

ELSA reports that female sex is a risk factor for the development of symptomatic knee osteoarthritis, with the prevalence being 17% in men compared to 20% in women. Not only are women more likely to develop osteoarthritis, but they are also more likely to develop severe osteoarthritis (Srikanth et al, 2005). Sex hormones were traditionally thought to play no role in joint health. Several relevant pathways have been investigated in recent years (Gokhale et al, 2004; Tanko et al, 2008; Sniekers et al, 2008). The homeostasis of the articular tissues are now thought to be under the control of oestrogen amongst other factors. The articular cartilage is under the control of oestrogen but so also may be the synovial fluid, synovium, bone and other periarticular tissues (Roman-Blas et al, 2009). Although observations on the increased incidence of osteoarthritis at the time of menopause have been made a large randomised controlled study found no effect from replacing the hormones (Nevitt et al, 2001).

ELSA reports the prevalence of arthritis to be 12% in people of healthy body weight (body mass index, 18.5-25) compared to 27.6% in those who are obese (body mass index > 30). The Framingham study demonstrated a 50% reduction in knee symptoms amongst women who had lost 5kg. The Framingham study also demonstrated that radiological progression of arthritis could be arrested by weight loss. Various other studies have supported weight loss

and exercise as a treatment for knee arthritis (Messier et al, 2004; Christensen et al, 2007). A complete appreciation of the effects of the recent obesity epidemic may not as yet have been fully calculated in relation to the development of knee arthritis.



**Figure 2. Population prevalence knee arthritis by risk factor from Arthritisresearchuk.org.**

Knee trauma and previous knee surgery have repeatedly been shown to be potent risk factors for the development of osteoarthritis (Lohmander et al, 2004). Meniscectomy, particularly total meniscectomy often precedes the development of osteoarthritis (Roos et al, 2001). Although it is not clear whether the meniscectomy or the original meniscal injury causes the osteoarthritis, the incidence of arthritis is thought to lower following partial meniscectomy as compared with open total meniscectomy. Several studies have questioned the validity of the meniscectomy. Although many patients experience reduced pain and increased functional levels following meniscectomy, the benefits have been compared to the benefits experienced by the placebo effect of a sham procedure (Hare et al, 2013).

The alignment of the lower limb is frequently referred to by surgeons planning treatments. The alignment is the key factor in distributing the load from body weight through the various joints. It is logical that malalignment may lead to a specific pattern of wear or arthritis, but this seemingly elementary observation has until recently been resistant to an evidence base. Sharma demonstrated that in unicompartament arthritis the deterioration would be accelerated in the presence of malalignment (Sharma et al, 2010). In more recent work the effect of malalignment on the incidence of arthritis has been demonstrated. The Rotterdam

study in 2664 knees demonstrated that arthritis was more likely to develop in a varus knee without arthritis than a neutrally aligned knee (Brouwer et al, 2007). The findings were significant in obese and overweight patients, but not amongst those of a healthy bodyweight. In later work with the MOST (Multicentre Osteoarthritis Study) in a longitudinal study of 2958 knees the same investigators demonstrated that although both varus and valgus alignment could accelerate arthritis. Only initial varus alignment could predispose the non-arthritic knee to arthritis (Sharma et al, 2010).

### The prevalence of patellofemoral arthritis

Patellofemoral arthritis is a very common condition, it may occur as part of arthritis of the entire knee or may occur in isolation. Changes are age related as healthy knee patella cartilage is known to reduce in volume at by 1-6% per year (Hanna et al, 2007; Cicuttini et al, 2002). The prevalence of patellofemoral arthritis has been described in the general population and in patients with symptomatic knee pain; the issue is complicated further by the existence of concurrent tibiofemoral arthritis in some cases. Noble’s famous 1975 study of 400 Scottish (mean age 65) cadaveric menisci (in 100 cadavers) includes a byline annotation that 79% of them also had patellofemoral arthritis .

Authors have studied the population in knee clinics. In 2002 Davies et al performed a radiological evaluation of the knee joints in 206 patients in an orthopaedic clinic, all over 40 years of age and complaining of knee pain. Of the studied population patellofemoral arthritis was present in 21.8%. In 9.2% this was isolated patellofemoral arthritis.

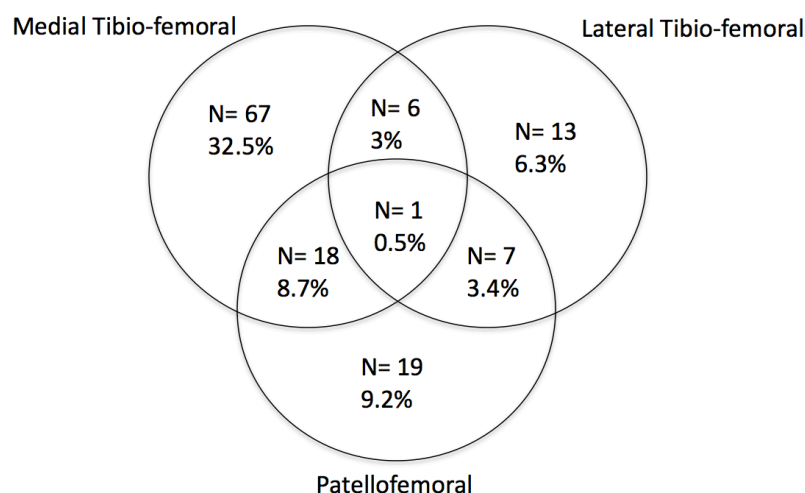


Figure 3. Site of osteoarthritis in knee clinic population. Davies et al 2002.

The most comprehensive examination of symptomatic patellofemoral arthritis in the community comes from Bristol. In 1992 McAllindon and Dieppe performed a cross-sectional

study of 2101 patients over the age of 55 from a general practice. Patients were sent a questionnaire and then those with knee pain (and a control group without pain) were asked to attend the Bristol Royal Infirmary for radiological assessment. They found that 53% of patients with knee pain had radiological evidence of arthritis and 17% of asymptomatic patients had evidence of knee arthritis. Amongst symptomatic patients, more of the women (24%) than men (11%) had radiological evidence of patellofemoral arthritis. Of the patients without knee pain; 3.8% had radiological findings of isolated patellofemoral arthritis, 0.6% of asymptomatic patients had some form of combined arthritis involving the patellofemoral joint. The authors estimated that the prevalence of symptomatic patellofemoral arthritis amongst men over 55 was 2% and for women over 55 was 8%.

There may be variation related to race, culture and geography. Asian populations have been demonstrated to have not only a high prevalence of tibiofemoral arthritis but also patellofemoral arthritis. One study in Southern Thailand found that amongst residents over 40 years of age the radiological prevalence of patellofemoral arthritis was 37.9% overall and 18% was isolated patellofemoral arthritis (Tangtrakulwanich and Suwanno, 2012). The study did not evaluate the population's symptoms.

### **Risk factors for symptomatic patellofemoral arthritis**

In the subsequent chapter a study evaluates the role of patellar instability as a risk factor for patella femoral arthritis. A structure literature review was performed, evaluating scientific literature with the following questions:

What are the risk factors for patellofemoral arthritis?

What makes patellofemoral arthritis symptomatic?

Does patellar instability play a role in the development of patellofemoral arthritis?

The employed search strategy included.:

1. Identification of search terms.
2. Predefined searching of internet based databases including Pubmed, Medline, google scholar, embase.
3. Citation chaining & pearl growing, review of the citations of each referenced paper to assess further literature. New key words may be generated as the search develops.

4. Search of the grey literature, generated through pearl growing of information from conference attendance and citation chaining.

Key search terms included: arthritis, patellofemoral, instability, dislocation, patellofemoral surgery, MPFL reconstruction, trochleoplasty, tuberosity distalisation, patellofemoral anatomy.

Identified articles were individually reviewed for relevance, reading the abstract of each. Where the article was relevant the full paper was attained and added to the review. In each case the references of each paper were reviewed and missing articles were reviewed. A total of 1,432 full text articles were attained and reviewed for the entirety of this thesis. The same search strategies have been deployed in each chapter of the thesis.

### **Risk factors for patellofemoral arthritis**

Tricompartmental knee arthritis and isolated patellofemoral arthritis may represent two different aetiologies. Many investigators propose that unicompartmental (medial tibiofemoral, lateral tibiofemoral or patellofemoral) arthritis is more likely to be associated with a specific biomechanical aetiology than is tricompartmental arthritis. Whereas the association between medial compartment arthritis and a varus limb alignment is well established the biomechanical factors at play in patellofemoral arthritis have been little investigated. Emerging theories include propositions that a development abnormality of the trochlea morphology or the length of the patella tendon may play a role (Liow et al, 2016; Stefanik et al, 2010).

The risk factors for symptomatic patellofemoral arthritis had received little attention in the literature until 1994. A second study from Dieppe's team in Bristol presented a small case controlled study evaluating the risk factors for symptomatic patellofemoral and medial compartment arthritis (Cooper et al, 1994). They evaluated 109 men and women with tibiofemoral and patellofemoral arthritis. They found stronger association between obesity, knee injury and meniscectomy with medial tibiofemoral arthritis. They found stronger associations between Heberden's nodes and family history of arthritis in the patellofemoral group. I consider this to be a landmark study, the author's objective being to evaluate the risk factors for arthritis in each part of the joint individually. I believe the major limitation of this study is that they do not evaluate the role of mechanical abnormalities of the patellofemoral joint, for example patella alta and trochlea dysplasia are not considered as risk factors. The findings of the study are that mechanical factors are more closely associated with tibio-femoral

arthritis. The mechanical factors that may affect the PFJ were poorly understood at the time of the writing of that paper. It is perhaps not surprising that as they only evaluated mechanical factors relevant to the tibio-femoral joint that they found a closer association between mechanical factors and tibiofemoral arthritis. As we now have a better understanding of the patellofemoral joint mechanics it is a natural next step to more accurately investigate what effect mechanical factors may have upon the development of patellofemoral arthritis.

In a knee clinic population of 174 patients Davies et al (2002) described some of the broad risk factors that apply to tricompartmental arthritis and found that they also apply to patellofemoral arthritis. They observed that the prevalence was greater with increasing age and contrary to expectation male sex. The study describes a population in a knee clinic rather than the general population and this may generate a bias that explains the unexpected finding of increased association with male sex. The relatively small size of this study when compared to other incidence studies does also increase the likelihood that these findings are due to chance. In their study, 36.1% of women and 32.7% of men over 60 had patellofemoral arthritis. Amongst those patients 13.6% of women and 15.4% of men had arthritis of the patellofemoral joint only.

Mcallindon et al (1996) used data from the Framingham Cohort study, including radiographs of 608 knees. They performed a multiple logistical regression looking at known risk factors for arthritis, and evaluated their relevance to isolated patellofemoral arthritis, tibiofemoral arthritis and tricompartmental arthritis. Risk factors evaluated included age, sex, BMI (body mass index), chondrocalcinosis and knee injury. The strongest association was with elevated BMI; overall, the tricompartmental arthritis had the strongest association with all risk factors. Chondrocalcinosis was not found to be associated with any pattern of knee arthritis. History of knee injury in men was not associated with patellofemoral arthritis but was with tibiofemoral arthritis.

Several authors have specifically examined the effect of various risk factors on the development of patellofemoral cartilage lesions. Cartilage injury is conventionally considered a precursor to osteoarthritis and there is some evidence to support this in clinical practice and the literature (Davies-Tuck et al, 2008b; Boegard et al, 2001; Ding et al, 2006; Wang et al, 2006). The outcomes of these studies of cartilage injury may not translate to osteoarthritis, much less severe symptomatic arthritis and the result should be interpreted judiciously. For completeness, they are presented here. Risk factors for patellofemoral cartilage degeneration have been evaluated in some detail by a group of researchers from Melbourne and by the investigators of the MOST study in Boston.

Teichtahl et al recorded the body mass of 297 healthy, ambulant and independent adults aged 50–79 years with no evidence of OA (Teichtahl et al, 2008a; Teichtahl et al, 2009). After ten years they evaluated the patellofemoral joint by MRI and evaluated risk factors for cartilage volume loss and injury. They demonstrated reduced cartilage volume and increased risk of cartilage injury amongst women with a high BMI.

In another publication from Teichtahl and co-workers in 2015 that included 250 people without knee pathology they studied the effect of weight loss on cartilage loss. Reduced fat content of the Vastus Medialis Oblique (VMO) muscle was found to correlate with a deceleration of both tibial and patella cartilage loss. Gunardi reported on 169 younger women (age 20-49), repeating the MRI after a ten-year period. They found that increased adiposity in young adults are associated with a detrimental effect on patella cartilage volume and the development of cartilage lesions. In 2005 Ding et al found that BMI was negatively associated with patella cartilage thickness and volume in a cross-sectional study of 372 people without clinical OA. In a cohort study from the same group, 148 women without clinical OA aged 40-67 underwent an MRI scan of the knee which was then repeated after two years (Wijayarathne et al, 2008). Interestingly, they did not find BMI to be correlated with cartilage loss. The authors found that physical activity was protective of cartilage loss. This is a cross-sectional study and it cannot assess the directionality of the effect, for example, thinned damaged cartilage may lead to exercise avoidance. The authors did not take account of patellar instability as a potential confounder.

Anterior knee pain in childhood as a risk factor.

Adolescent anterior knee pain is usually considered to be a self-limiting disease without long term effect (Insall, 1984). Several studies have found that anterior knee pain may have long lasting effect. The two largest longitudinal studies (Nimon et al, 1998; Stathopulu and Baildam, 2003) followed-up the patients for 4-20 years. They found that 20-45% continued to experience pain and 36% had to restrict their activities. Unfortunately, the follow-up stopped prior to the age at which arthritis might be expected to manifest so they are of limited value. A retrospective study by Utting et al (2005) is discussed below.

Patellar instability as a risk factor

The patella and trochlea have corresponding cartilage that are designed to meet at specific points of flexion and transmit the differing loads that occur during flexion. The less congruent joints have thicker cartilage, this may be a response to the forces that are generated through them (Shepherd and Seedhom, 1999). The loss of congruity and dislocation or



impending dislocation is experienced by the patient as instability. Instability represents a constellation of symptoms which ranges from the knee collapsing during walking to a sense of distrust of the knee and high-risk activity avoidance. This tenuous relationship and interplay between very heavily loaded cartilage and instability may play some role in the symptoms generated by arthritis of this joint.

The experience of patients with patellofemoral arthritis were recorded in a case controlled study from the Winford Unit (Utting et al, 2005). Utting and Newman surveyed 150 patients who had undergone patellofemoral arthroplasty and 150 patients who had undergone unicompartment knee replacement. They found adolescent anterior knee pain was more common amongst the patellofemoral group (22% vs 6%) and that a greater proportion of those patients had also experienced patellar instability (14% vs 1%). The study cannot tell us whether the instability causes the arthritis, or whether both the arthritis and the instability share a common risk factor.

Sanders in Minnesota undertook a longitudinal study out to 25 years (Sanders et al, 2017). They examined the medical notes of 609 patients with a history of patella dislocation and compared them to a control cohort. They defined patellofemoral arthritis as a history of patellofemoral symptoms coupled with radiological signs of arthritis. They found an incidence of arthritis of 48.9% of arthritis in the dislocation group at 25 years compared to 8.3% in the control group a hazard ratio of 7.8. There was no increased incidence of knee arthroplasty- this is likely due to the young age of these patients. Unlike the Utting study the methodology of this paper does not permit it to separate out clinically relevant arthritis.

Risk factors for patellar instability may also be risk factors for patellofemoral arthritis. Trochlea dysplasia is known to be associated with patellofemoral arthritis (Newman, 2007) and has been reported to be present in up to 50% of cases of patellofemoral arthritis (Newman, 2006). One MRI study found the presence of dysplasia was associated with a reduced overall cartilage volume, what this means for the development of arthritis remains unclear (Jungmann et al, 2013). In 2015 Liow et al studied the outcomes of patellofemoral replacement and found that the absence of trochlea dysplasia and obesity were linked to progression of the arthritis and development of tibiofemoral arthritis. This finding fits well with the concept that patellofemoral arthritis may be caused by biomechanical factors specific to the patellofemoral joint, and that in those patients tibiofemoral joint arthritis is not inevitable.

In 2008 Davies-Tuck et al in Melbourne used interval MRI over a two-year period in 100 patients with knee arthritis to evaluate the effect of sulcus angle on cartilage volume. They found that where the trochlea sulcus was flatter the patella was thicker. No relationship between

arthritis progression and trochlea morphology was identified in these patients with tricompartmental knee arthritis. In 2007 Teichtahl used a similar methodology with 297 healthy knees, no relationship was found between trochlea dysplasia and cartilage lesions .

Kalichman (2007) performed a cross-sectional study of patients in the Boston Osteoarthritis of the Knee Study (BOKS), they looked at a number of recognised patellofemoral indices and related these to the appearance of cartilaginous and bone lesions on MRI. The study included 126 males (mean age 68.0, BMI 31.2) and 87 females (mean age 64.7, BMI 31.6). They found an association between both severity of patella alta and trochlea dysplasia (measured by sulcus angle) with the presence of lateral patellofemoral cartilaginous lesions.

Several investigators have performed biomechanical studies and proposed that variations in the length of the patella tendon alter not only the contact between patella and the trochlea, but also the forces passing through the joint (Yamaguchi and Zajac, 1989; Hirokawa, 1991; Meyer et al, 1997; Ward et al, 2005; Luyckx et al, 2009).

Luyckx used a dynamic knee simulator jig to evaluate the effect of patella height on cartilage pressures (Luyckx et al, 2009). Patella height is described as patella alta where the patella tendon is long and the patella is high, it is termed baja when the patella tendon is short and the patella is low. Luyckx found that the increasing pressure that was noted as the knee flexed was delayed in the patella alta group; however, the pressure ultimately peaked above that in the normal patella height group. This finding would appear consistent with the report given by patients of increasing anterior knee pain after sitting for long periods.

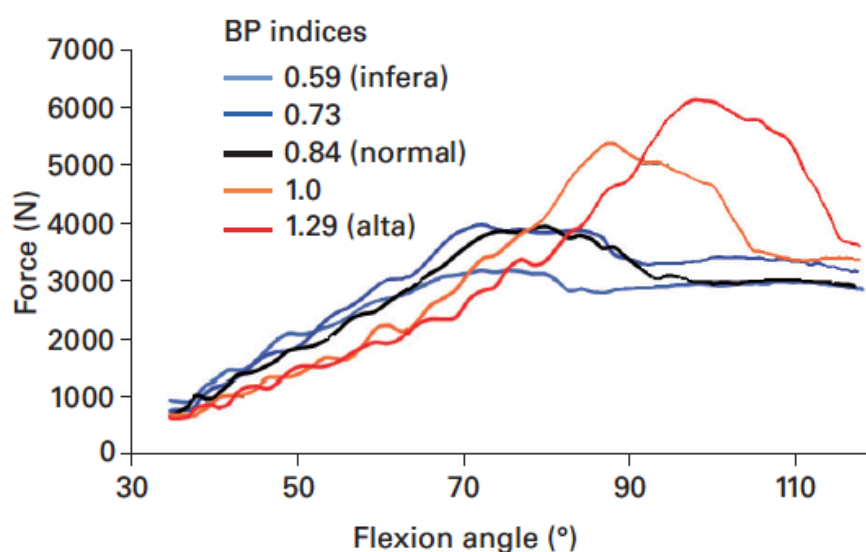


Figure 4. Effects of varying patella height on contact pressures in differing knee positions (BP=Blackburne-Peel index). Image from Luyckx et al, 2009.

The MOST study reported on the relationship between patella alta and MRI features of patellofemoral arthritis. This large longitudinal study reported on 907 knees (mean age 62, BMI 30, Insall-Salvati Ratio (ISR) 1.10). They compared MRI findings at base line with those at 30 months. They measured patella height with the ISR and compared knees in the lowest and highest quartile of ISR. At the baseline, those in the highest quartile had 2.4 (95% CI 1.7, 3.3) times the odds of having lateral PFJ cartilage damage. They also found changes deteriorated over time.

In 2009 Ali et al. evaluated symptomatic knees and measured patella height by a number of techniques. They evaluated 103 knee MRIs amongst patients with knee symptoms. The data is retrospective and represents a variety of different knee pathologies. They found cartilage lesions amongst patients with patella alta but could not correlate severity of patella height with severity of chondral lesion. There are several limitations to this study. Initially the examined group do not necessarily complain of any anterior knee pain symptoms and as such the examination of these patients may be irrelevant. They do not standardise the knee position and the measurements they are subject to the effects of this. It is not surprising for these reasons that they found no differences, the ill-defined patient group, variety of pathologies and poor measurement technique would certainly overwhelm any differences.

A Finish study (Salonen et al, 2017) attempted to evaluate the long term outcome for the patellofemoral cartilage of patients who had experienced a single dislocation. They compared the MRI scan of patients who had undergone a first patella dislocation with a further scan several (mean 8) years later. Of the 20 patients in the study 70% demonstrated cartilage injury at initial presentation. At final review all had a cartilage abnormality, 50% having a severe cartilage lesion. This longitudinal study is limited in that it only follows patients for eight years and that it has no control group- some degeneration of cartilage might be expected as a result of the patients normal activities. The study does not explore the effects of the anatomic differences of these patients or the joint congruity.

#### Patella stabilisation surgery as a risk factor

A Swedish study examined the effect of patella stabilisation surgery on the development of arthritis (Arnbjornsson et al, 1992). The authors followed up 29 patients who had bilateral patellofemoral joint instability. For inclusion, each patient had to have experienced at least two dislocations of both patellofemoral joints. In each case one side had been operated and the other treated by physiotherapy alone. The surgery performed included re-tensioning of the knee joint capsule with or without medialisation and distalisation of the

tibial tuberosity. They found that the rate of redislocation was higher amongst the operated group as was rate of osteoarthritis. They concluded that the operations they had used provided only a short-term benefit. Schuttler's 2014 study followed a cohort of patients with a history of patella dislocation who had undergone a stabilisation of the patella by an "Insall procedure". They followed 42 patients for a mean of 52 months, evaluating the patellofemoral joint by MRI scan at time of surgery and at final follow-up. They found that the number demonstrating signs of arthritis of the patellofemoral joint rose from 4 to 18, noting more rapid progression amongst those with trochlea dysplasia. This cohort study has no randomisation, yet they concluded that the procedure had led to arthritis. The conclusions are not merited as the role played by the natural history of the instability is un-quantified, and a causality link is not established with the study methodology used.

#### Quadriceps musculature as a risk factor

Surgeons and physiotherapists frequently note wasting of the quadriceps muscle in cases of patellar instability and arthritis; rehabilitation of this muscle group makes up a part of physiotherapy treatment. Several authors have noted the association between patellofemoral pain syndrome and quadriceps wasting (Callaghan and Oldham, 2004). In a 2013 report from the MOST study Stefanik evaluated the role of quadriceps weakness and patella alta on the development of patellofemoral bone marrow lesions. A total of 807 knees with evidence or risk of OA were examined by MRI and a dynamometer. They found a correlation between patellofemoral bone marrow lesions and quadriceps weakness, they also found a correlation between patella alta and bone marrow lesions. In a further study, they found that combining those risk factors did not appear to magnify the effect (Stefanik et al, 2011).

Berry et al from the Melbourne group published an unexpected finding in 2008 when evaluating 175 women aged 40-67 with asymptomatic knees. They found that there was an association between vastus medialis cross-sectional area and both patella cartilage defects and patella bone volume. There are several limitations of this study, not least that the imaging is that of a typical knee MRI and so only the distal part of the knee is examined. They did not consider what effect other mechanical abnormalities may have on the position of the muscle that they are measuring. They comment that the increased musculature associated with degenerative changes are may be compensatory mechanism and that further longitudinal studies are required. The study is in contrast the remainder of the literature, as the authors do not appear to consider what effect the mechanics of the joint may play we are left contemplating if the findings are credible.

### Coronal alignment as a risk factor

A Canadian group investigated the effect of varus and valgus tibiofemoral alignment on patella kinematics in 10 knees with arthritis. They found potent effects particularly on the patella in the coronal plane, more medial PFJ arthritis in varus alignment and lateral PFJ arthritis in valgus alignment (McWalter et al, 2007). A group from Melbourne investigated the effect of coronal plane mal-alignment on the development of patellofemoral osteoarthritis (Teichtahl et al, 2008b). They recruited 99 patients with symptomatic knee OA and performed MRI and interval MRI at 2 years. They found a potent association with a dose relationship between valgus alignment and loss of patella cartilage. The findings are interesting as they partly explain the development of patellofemoral OA in cases of tibiofemoral OA.

### Anterior cruciate ligament reconstruction as a risk factor.

Several authors have observed patellofemoral arthritis following anterior cruciate ligament reconstruction (Bourke et al, 2012; Ahn et al, 2012; Leys et al, 2012; Murray et al, 2012; Keays et al, 2010; Cohen et al, 2007; Keays et al, 2007; Salmon et al, 2006; Hertel et al, 2005; Lohmander et al, 2004; Breidfuss et al, 1996). Several mechanisms have been proposed. In some cases, the central third of the patella tendon is harvested as a graft for the anterior cruciate ligament (ACL) and it may be anticipated that this would cause some patellofemoral dysfunction. Two authors found that the prevalence of patellofemoral arthritis is higher when a patella tendon graft is used rather than a hamstring graft (Keays et al, 2007; Li et al, 2011). Keays and co-workers found arthritis in 41% of cases where patella tendon graft had been used compared to 30% amongst hamstring grafts. Li's findings are comparable with rates of 30% and 16%. The differences were not statistically significant. A more likely explanation is the increase in abnormal forces experienced by the ACL deficient knee, particularly tibial rotation leading to cartilage shear in the patellofemoral compartment. Normal biomechanics are not consistently restored by ACL reconstruction (Gao and Zheng, 2010; Georgoulis et al, 2007; Webster and Feller, 2011). Other proposed mechanisms include cartilage softening as part of an inflammatory healing process, loss of knee extension leading to exaggerated patellofemoral forces and quadriceps dysfunction (Culvenor et al, 2013).

### Floor activities as a risk factor

As the knee flexes, the forces transmitted through the patellofemoral joint are known to increase (Luyckx et al, 2009). Authors have proposed that kneeling, squatting, lotus position seating or side-knee bending may increase the risk of patellofemoral arthritis (see figure 5).

The greatest experience and interest comes from Asian authors where floor sitting form a greater part of the culture and activities of daily living.

In 2007 Tangtrakulwanich et al performed a cross-sectional study of Thai adults over 40 without a history of major knee trauma or rheumatoid arthritis, evaluating the effect of floor activities. Amongst the 288 women and 288 men in the study they found that the patients spent an average of 56 minutes per day on the floor. They identified a close relationship between lifetime risk of floor activities and development of combined pattern (patellofemoral with tibiofemoral) arthritis. No relationship was found between isolated patellofemoral or isolated tibiofemoral arthritis and time spent on floor activities.

The authors used a similar methodology with a sample of 261 Buddhist monks and found no association between floor activities and knee osteoarthritis (Tangtrakulwanich et al, 2006). One of the interesting challenges faced by this study is in its use of patient's memory. The authors reflect on how current knee pain and arthritis could influence how the patients remember their lifelong floor activities. A significant confounder that these studies face is inactivity and associated obesity, itself a risk factor for arthritis; patients who are less active spending more time on the floor. Ultimately the effect of floor sitting is not a factor that is significant within our studied population.

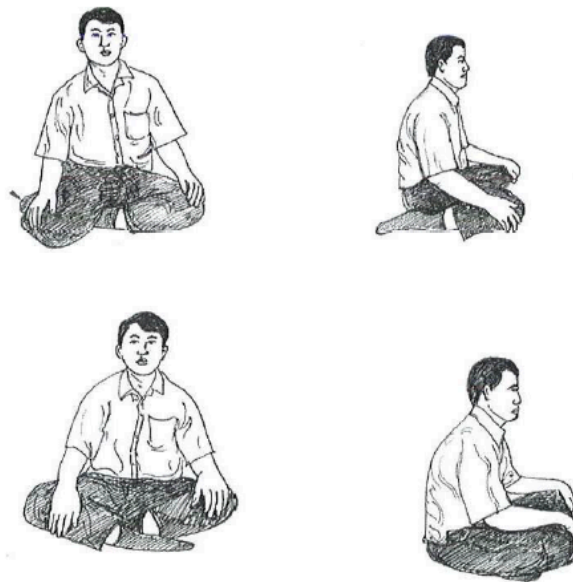


Figure 5. Side bending knee (top) and lotus (bottom) from Tangtrakulwanich et al, 2007.

### What make patellofemoral arthritis symptomatic?

Given the very high prevalence of patellofemoral arthritis (may be as high as 79% in the elderly, Noble and Hamblen, 1975) and the smaller proportion who are symptomatic (2-

8% in those over 55, McAlindon et al 1992), the cause of the symptoms may not be simple cartilage bearing loss.

The ABC health study sought to evaluate factors that would accelerate the progression of patellofemoral arthritis and that would lead to painful arthritis (Hunter et al, 2007). They identified that patella subluxation was related to progression in that direction, i.e. lateral subluxation was related to lateral arthritis. They also identified that lateral subluxation was related to increased pain scores.

Stefanik used both MOST and Framingham Osteoarthritis Study data to correlate the site of MR identified bone marrow lesions and cartilage lesions with symptom severity (Stefanik et al, 2015). Bone marrow lesions in either facet were associated with knee pain. They found that isolated medial facet cartilage loss was not associated with pain. Lateral facet cartilage lesions and mixed (both medial and lateral facet) lesions both had a 1.9 odds ratio of pain. The findings point towards the importance of lateralising forces not only in generating cartilage loss but also generating symptoms.

In a separate study 2014 study Stefanik asked a related question: Do anterior knee symptoms predict patellofemoral cartilage injury? They presented the sensitivity, specificity, positive and negative predictive values for presence of anterior knee pain, pain with stairs, absence of pain while walking on level ground in determining location of cartilage injury (patellofemoral or tibiofemoral). They evaluated 407 knees where the patient had expressed pain, aching, or stiffness in the past year. Anterior knee pain had a sensitivity of 60% and specificity of 53%, whereas isolated anterior knee pain had a sensitivity of 27% and a specificity of 81%. “Absence of moderate pain with walking on level ground” had the greatest sensitivity (93%), as most PFJ OA patients reported this, however, the question was also answered positively by most normal knee and tibiofemoral OA knee patients and so had a poor specificity (13%). Even pain on stair descent only had a sensitivity of 64% and specificity of 40%. They concluded that none of the self-reported pain variables performed well as a diagnostic test for PFJ structural damage. The poor sensitivity of stair descent is an interesting finding, indication that not all damaged joints generate symptoms even when loaded.

The scientific literature suggests that pain from PFJ arthritis is not simply a factor of the arthritis. The concept of misalignment and abnormally high joint forces contributing to pain is suggested in these studies. PFJ instability results as a severe form of PFJ malalignment and this risk factor merits further attention.

## **Patellar instability an introduction:**

Gray's anatomy states that "As the leg is extended from the flexed to the extended positions, first the highest pair, then the middle pair and lastly the lowest pair of the horizontal facets are brought successively into contact with the patella surface of the femur". Loss of this relationship defines patellar instability.

In a consensus statement from American Orthopaedic Society for Sports Medicine (AOSSM) and the American Patellofemoral Foundation (PFF) they defined patella stability and instability:

"We define patellofemoral stability as constraint by passive soft tissue tethers and chondral/bony geometry that, with muscular forces, guide the patella into the trochlear groove and keep it engaged within the trochlear groove as the knee flexes and extends." (Post and Fithian, 2018)

"Furthermore, we define patellofemoral instability as symptomatic deficiency of the aforementioned passive constraint (patholaxity) such that the patella may escape partially or completely from its asymptomatic position with respect to the femoral trochlea under the influence of displacing force. Such displacing force could be generated by muscle tension, movement, and/or externally applied forces." (Post and Fithian, 2018)

## **Diagnosis of patellar instability (dislocation & maltracking)**

Diagnosis is made on the basis of patient history, examination and investigations with evaluation of the cross-sectional anatomy.

The terminal end of the instability spectrum is dislocation, the dislocation is transient and by the time the patient see the physician is often reduced. Patients present to the physician with characteristic history of knee instability, the history can be extremely similar to that of a rupture of the anterior cruciate ligament, the knee giving way after twisting. Physical examination and evaluation of the anatomy on imaging indicates the underlying cause of the dislocation. Sometimes latent effect of the dislocation can be seen on the MRI scan with bone bruising of the medial patella and lateral femur where abnormal contact occurs during dislocation.

Maltracking is a poorly defined condition at the less severe end of the instability spectrum, patients present with a feeling of unease in the front of the knee. They may have never dislocated the patella. Physical examination and evaluation of the anatomy on axial imaging demonstrates an incongruent joint and underlying anatomical abnormalities which



may include injury to the MPFL, patella alta or trochlea dysplasia (definitions of these in chapter 2).

### **Incidence of dislocation and recurrent dislocation**

The largest data set comes from a series of studies of a health insurance plan population in the United States (Fithian et al, 2004; Atkin et al, 2000). Sixty-nine percent of individuals with first time patella dislocations are between the ages of ten and nineteen (Atkin et al, 2000). The overall risk of dislocation was 7 per 100,000 per year, and in the second decade of life this rose to 31 per 100,000 (Atkin et al, 2000). A Finnish study calculated an incidence of 43 per 100,000 in children under 16 years (Nietosvaara et al, 1994).

The recurrence rate in all-comers to non-operative treatment was reported in Stefancin's 2007 systematic review as 38–57% with a mean of 48%. If a patient dislocates the patella for a second time the rate of recurrence is then higher (Fithian et al, 2004). Several authors describe patella dislocation, like shoulder dislocation, to be more likely to recur amongst the young (Buchner et al, 2005; Larsen and Lauridsen, 1982; Cash and Hughston, 1988). Buchner found patients younger than 15 years had 52% recurrence rate as compared to 26% in their overall sample (Buchner et al, 2005). They found that most recurrent dislocations occurred within one year of the first dislocation and there was a risk of contra-lateral patellar dislocation in 10%. Patella dislocation is the second most common cause of haemarthrosis of the knee (Harilainen et al, 1988).

Fithian et al reported a 2-5 year follow-up after primary dislocation and performed a logistic regression and evaluated risk factors for recurrent dislocation (Fithian et al, 2004). They included age, sex, prior dislocation, family history of patella problem and risk factors for developmental dysplasia of the hip (DDH) in the model. Previous dislocation carried an odds ratio of 6.6, risk factors for DDH carried an odds ratio 0.51 but did not reach significance.

A study from the Mato clinic of 222 knees in 210 patients with a history of patella dislocation evaluated risk factors for recurrent dislocation in the adolescent population. They found that age, sex, body mass index and patella alta were not independent predictors of recurrent dislocation. Where trochlea dysplasia and an open physis was present the recurrent dislocation rate was 69% (Lewallen et al, 2013). Lewallen's findings are interesting, they most recurrences occur in the first year except in the case of dysplasia patients where early survival is not a good predictor of later stability. There are some limitations to this study, one year follow up was only 75% so the actual recurrence rate may be much higher. We must also take

into consideration that risk factors for re-dislocation may be different in chronic instability rather than in the initial scenario. The authors of this study suggest that this might explain the lack of association with patella alta.

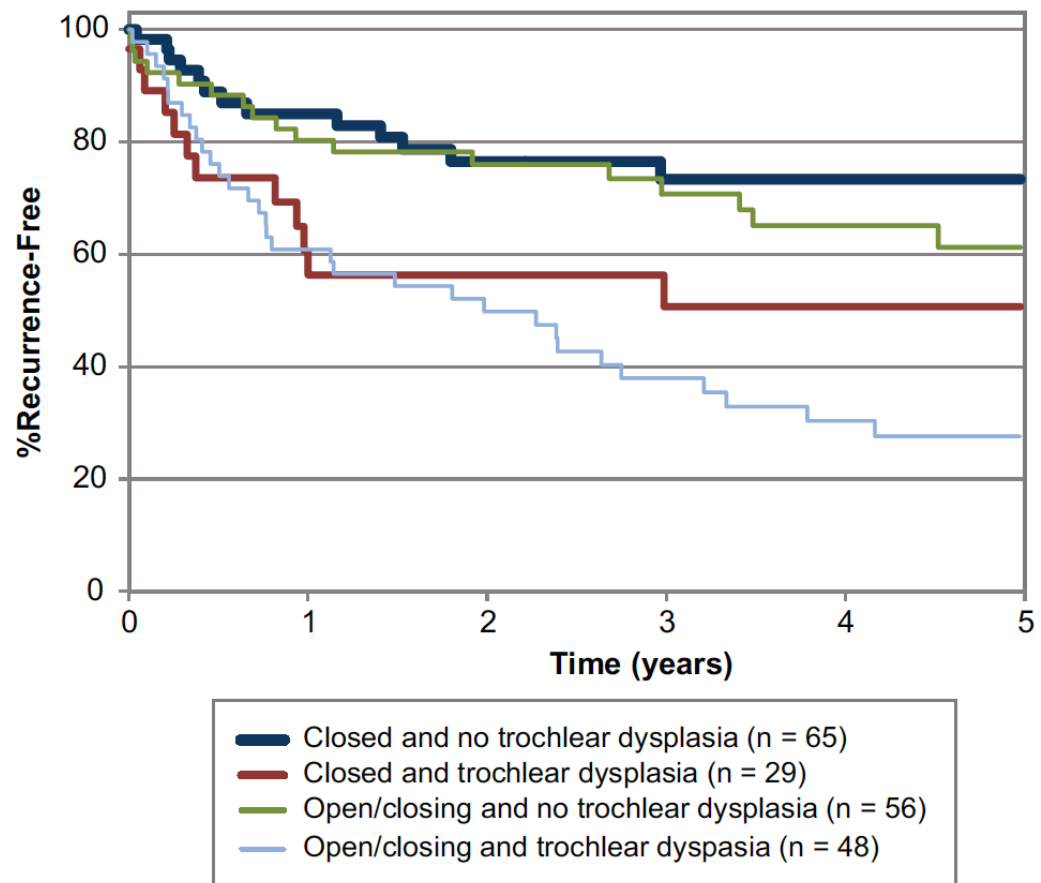
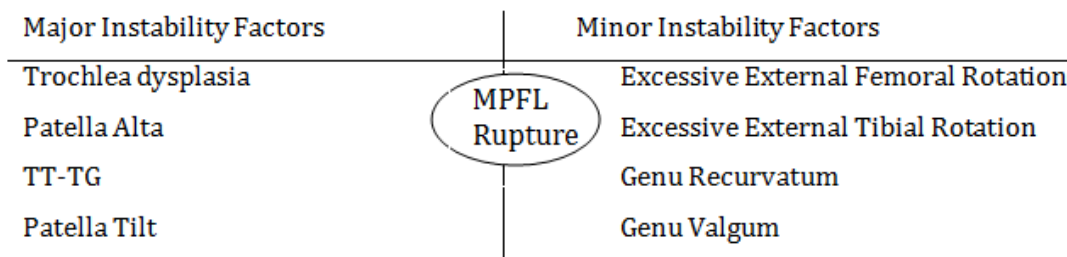


Figure 6. Survival of joint stability to first dislocation by presence of dysplasia and skeletal maturity. Image from Lewallen et al 2013.

### Risk factors & anatomy of patellofemoral instability

It has been proposed that the major anatomic factors implicated in patellar instability include trochlea dysplasia, patella alta, lateral placed tuberosity and patella tilt (Dejour et al, 1994). Their explanatory table has been reproduced below. They also recognise the importance of secondary MPFL rupture and various minor factors. Unlike the other anatomic factors patella tilt is a dynamic product of the relationship of the patella and femur. It probably should not be included in the table as a cause of instability, it is likely secondary to the other causes.



**Table 3. Dejour’s description of minor & major instability factors. Image reproduced from Dejour (1994).**

### Joint laxity

Several authors have described a high prevalence of hypermobility amongst patients who have suffered a patella dislocation (Howells and Eldridge, 2012; Wolf et al, 2011). The prevalence of hypermobility in the general population may be as high as 10% to 20% (Ross and Grahame, 2011). In 1983 Rünow used a case controlled methodology to describe a six times higher incidence of patella dislocation amongst those with hypermobility. Bilateral instability was also more common amongst these patients. Patients with hypermobility may enjoy some protection from osteochondral injury (Stanitski, 1995).

In a recent consensus statement from American Orthopaedic Society for Sports Medicine (AOSSM) and the Patellofemoral Foundation (PFF) the importance of this condition is acknowledged:

“Patholaxity can be due to genetic predisposition (as with hyperlaxity conditions) or as a result of trauma. Patellar instability is a symptom that requires patholaxity for the patella to escape partially or completely from its asymptomatic stable position. Symptomatic patellar instability happens only when there is patholaxity. Symptoms of patellofemoral instability can be episodic because even in the presence of patholaxity, neuromuscular control and articular congruity can maintain the physiologically adequate position of the patella and trochlear groove relative to each other.” (Post and Fithian, 2018)

### Dejour’s major anatomical factors

Trochlea dysplasia is defined as abnormal trochlea shape, any congenital or developmental morphologic abnormality that prevents the trochlea from performing its function of transmitting the patella forces. The measurement of this condition is detailed in chapter 2. It is commonly found amongst patients who have experienced patella dislocation. In 1994 Dejour reported that trochlea dysplasia is present in 96% of 143 patients who have undergone surgery for patella dislocation and in only 3% of patients who have not. The trochlea groove has the function of offering a channel through which the patella may pass and a surface

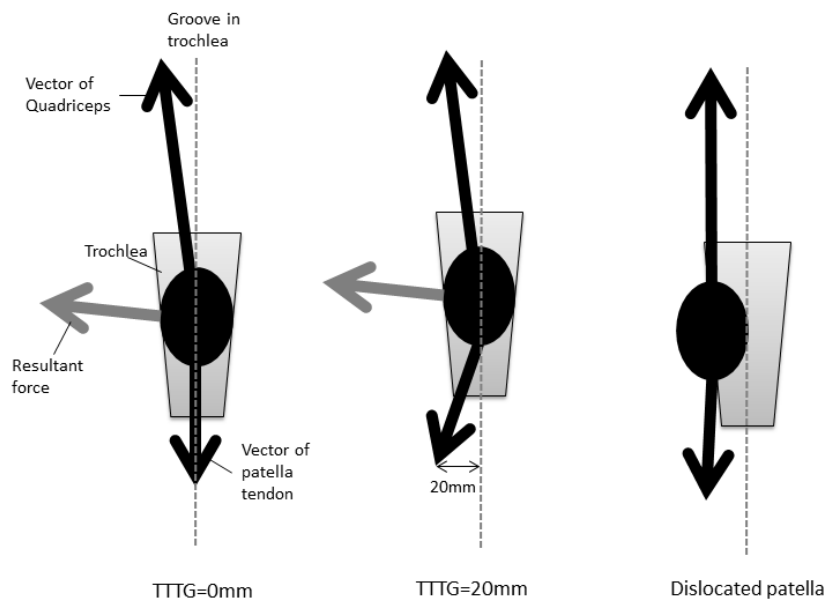
against which it may transfer force (Dejour D, 1998; Lippacher et al, 2012). The shape of the normal trochlea offers some resistance against dislocation of the patella and by offering a matched surface to the patella it enables a larger surface area for transmission of forces.

Patella alta is defined as an abnormally high patella, usually as a result of a longer than normal patella tendon. The higher patella does not engage in the trochlea as the knee bends and is more prone to dislocation. The measurement of patella alta is described in chapter 2. Patella alta appears to be a potent risk factor for patellar instability, it may be found in 50-60% of cases with a primary dislocation (Atkin et al, 2000; Steensen et al, 2015). Patella alta frequently co-exists with trochlea dysplasia (Metcalf A, 2015; Steensen et al, 2015). The explanation remains unclear, but it may be that the alta has a moulding effect on the trochlea, similar to the cause-effect postulated by Øye et al in 2015 for babies in frank breech.

Tibial tubercle to trochlea groove distance (TTTG) measures the offset between the path of the patella through the trochlea and the distal insertion of the patella tendon, see figure 7. It is an indirect quantification of the Q-angle (discussed further in chapter 2). Walch et al (1987) demonstrated an increased frequency of patella dislocation when the TTTG exceeded 10mm.

In a 2011 case controlled study, Balcarek evaluated the TTTG amongst children and adults (age range 10-47). The cases included people who had experienced a patella dislocation, the definition of dislocation required that some latent evidence of the dislocation (bone bruising or fracture) be evident on the MRI scan. Overall they found the TTTG to be 4mm greater amongst 109 patients (14.6 mm) with a history of patella dislocation when compared to 136 controls (10.6mm). They performed a multivariate analysis and found that increased TTTG was a risk factor for dislocation independent of patient age. The findings were statistically significant, although the measures may be small (10.6 vs 14.6mm) the study indicates that these minor discrepancies may be clinically significant.

The insertion of the patella tendon into the tibia is lateral to the trochlea groove. The origin of the quadriceps musculature is also largely lateral to the trochlea groove. This results in a lateral vector acting on the patella and is the driving force behind dislocations.



**Figure 7. The dislocated patella resolves the lateralising force of the quadriceps. The image on the left demonstrates the normal scenario, the middle image demonstrates an increased TTTG but not dislocated. The image on the right demonstrates the lateralising forces resolved after the patella has dislocated.**

Steensen published a case controlled study in 2015 which had evaluated the prevalence of the “major” anatomical abnormalities amongst patients with and without a history of recurrent patellar instability. They found all factors to be more common amongst the recurrent instability group including patella alta with an  $ISR > 1.2$  (60% vs 21%), trochlea dysplasia defined as a flat or convex trochlea (68% vs 6%) and a TTTG of more than 20mm (42% vs 3.2%). Multiple factors were identified in 58% of the patients with recurrent instability.

#### MPFL rupture

The medial patellofemoral ligament (MPFL) contributes 60% of the static restraint to dislocation of the patella in the normal knee and is the primary stabiliser when the knee is in full extension to 30° of flexion (Desio et al, 1998). This elongated fan shaped ligament inserts along the medial border of the proximal two thirds of the patella and onto the femur within the triangle created by the adductor and gastrocnemius tubercles and the surgical medial epicondyle. In the adult, it is approximately 55mm in length, it is a relatively elastic ligament and fails at up to 49% of strain as compared with the posterior cruciate which fails at 18% (Mountney et al, 2005; Jacobi et al, 2012). Due to the large excursion of the dislocated patella, the MPFL it is ruptured or avulsed and rendered incompetent after 90% of patella dislocations. . It is most commonly injured at the femoral origin amongst adults, whereas the injury is usually on the patella side in children and frequently includes an avulsion fragment (Felus and Kowalczyk, 2012).

### Dejour's minor anatomical factors

Dejour et al (1994) describes excessive external femoral rotation, excessive external tibial rotation, genu recurvatum and genu valgum as minor instability factors. In contrast Atkin's (2000) examination findings including limb alignment and hip rotation were not significantly different when compared to normal published values or the contralateral limb. Although these factors did not meet statistical significance this may be due to their rarity rather than lack of clinical significance and must remain a consideration. Smith et al (2012), examined the intra-observer and inter-observer reliability of 18 different examination findings. They found poor reliability between intra and inter rater assessment of most the physical examinations specific to the patellofemoral joint, .

### Clinical presentation in infancy and adolescence:

Several authors have attempted to classify the clinical presentation of infantile patellar instability leading to complex and overlapping classifications. Chotel (2014) adapted Dejour's(1994) and Garin's (1994) work to describe five distinct clinical presentations: congenital dislocation, permanent dislocation, habitual dislocation in flexion, habitual dislocation in extension and episodic dislocation (Ghanem et al, 2000; Wada et al, 2008). Parikh's recent classification includes a numeric designation; it may be a helpful communication tool though it does not add to the management as the categories are largely nominal (Parikh and Lykissas, 2016).

Fulkerson's 1997 description of infantile patella dislocation as congenital or acquired may be more helpful. Infantile dislocation is distinct from the adolescent form with characteristic osseous abnormalities including a small or absent patella, hypoplastic trochlea, external tibial torsion, tight quadriceps and thickened lateral structures (Chotel et al, 2014). It may be associated with Larson syndrome, arthrogryposis, diastrophic dysplasia, nail-patella syndrome, Down's syndrome and Ellis-van Creveld syndrome (Ikegawa et al, 1993; Mizuta et al, 1994; Dugdale and Renshaw, 1986).

Amongst adolescents and young adults patellar instability may present with a dislocation or a range of other symptoms. The patella may not dislocate at all, patients presenting simply with a sense of discomfort and unease with "something out of place" in the knee (Reider et al, 1981).

### Congenital or developmental

Precisely what initiates the pathway to abnormal anatomy and instability remains unclear. Although instability has been previously demonstrated to have a familial association in 15% of cases, the inheritance patterns have not been identified to date (Crosby and Insall, 1976). Anatomical risk factors may be evident in utero. Several authors described the formation of the patella in some detail (Glard et al, 2005b; Glard et al, 2005a; Walmsley, 1940; Gardner and O'Rahilly, 1968). Soon after the limb bud appears at four weeks the quadriceps muscle can be identified but the motor unit is undeveloped and the knee remains at a right angle. At seven weeks, the first evidence of a patella condensation is evident between the quadriceps and the femoral condyle. By thirteen weeks of development the femoral condyles have a similar geometry to the adult knee, and by 23 weeks the lateral patella facet is dominant. Some authors have postulated this as evidence of a genetic basis of patellar instability (Fulkerson et al, 1997).

The sulcus angle of the trochlea was evaluated by Øye and colleagues in a 2014 and 2015 study, using ultrasound in 348 neonates. Defining trochlea dysplasia as an angle of  $>159^\circ$  they identified trochlea dysplasia in 17 cases. Using a case controlled methodology, they identified an odds ratio of 15 for the presence of trochlea dysplasia in neonates who had been in frank breech (with the knees held in full extension in utero). This moulding hypothesis is in contrast with a genetic aetiology. No study to date has demonstrates translation of these findings into clinically relevant dysplasia later in life.



**Figure 8. The neonatal trochlea as seen in this ultrasound image. Image courtesy of Christian Øye (personal communication).**

Patellofemoral indices in the developing joint:

Age is a significant consideration amongst these patients. The condition often presents as the joints and limbs are undergoing rapid growth in adolescence. The joint is not just increasing in size but appears to undergo morphologic changes in this time. Dickens (2014)

described tibial tubercle-trochlear groove (TTTG) distance increasing with age as a natural logarithm and plateauing at 16 years. In 2014 Kim et al also studied the developing joint. They found no significant variation in trochlea facet asymmetry, trochlear depth, TTTG or patellar height ratio in 97 children age 5-22. This study has been criticised as most of the children were over 10 years old and half of those had undergone closure of the femoral physis.

Mundy (2016) performed a large study of 144 near normal knee MRI's in children aged between 1 and 16. They assessed TTTG, patella height and various measures of trochlea morphology. The measurements from younger children differed from those of adults, having a shallower trochlea, greater sulcus angle more medial tuberosity and a smaller patella height ratio.

The absolute values of patellofemoral indices can be expected to increase as the joint increases in size, but the changes in sulcus angle and patella height ratio point to age dependent morphology.

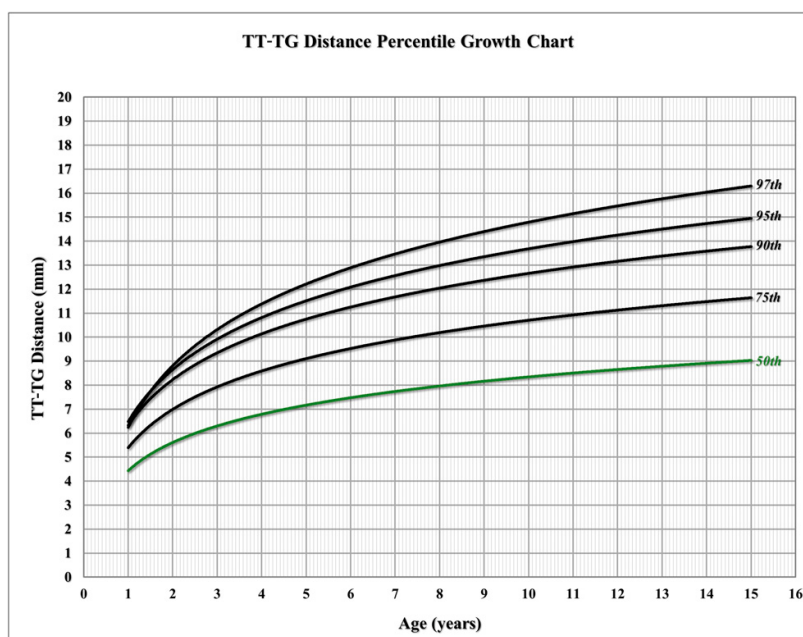


Figure 9. The TTTG distance develops with age. Image from Dickens et al, 2014.

### The treatment of patellar instability

Historically some surgeons will use a single operation to address patellar instability regardless of the pathoanatomy. Increasingly, those with an interest in this problem promote an approach where the particular pathoanatomy is identified and addressed (Andrish, 2008; Colvin and West, 2008; Mulford et al, 2007).

Lateral release and medial reefing



This approach has been very popular since it was first described by Merchant and Mercer. This procedure is easy and fast to perform; a significant number of patients do well for several years and it became very popular amongst orthopaedic surgeons. Small studies have been supportive of the procedure whilst helping to identify weaknesses (Simpson and Barrett, 1984; Bigos and McBride, 1984). The procedure may exacerbate the pain in patients with hypermobility, if the release extends proximal to the patella the vastus lateralis may be released, thereby causing medial instability. In a 2007 systematic review Latterman et al found the procedure to have a high failure rate, few studies had follow-up beyond eighteen months and those that did demonstrated poor results. Where studies followed patients for less than four years there was a satisfactory outcome in 80% of cases compared to just 64% when follow-up for more than four years.

#### Tibial tuberosity transfer:

A number of historical variations exist but the osteotomy most commonly used now is to move the tibial tuberosity inferiorly, medially and anteriorly (Fulkerson, 1983). This procedure has been a success for patients where the distal osseous anatomy contributes to instability, and when patients have pain due to distal lateral facet cartilage damage (Fulkerson, 2002). Anteriorisation of the osteotomy may provide some off-loading of the patella cartilage and is used where damage is already present. Several authors have published on the use of the tuberosity transfer for instability; some finding this an effective treatment with universal improvement in knee scores and no further dislocations (Barber and McGarry, 2008). In 2002 Nakagawa et al found a 91% good to excellent result at first follow-up which fell to 64% at final follow-up, they attribute this to their inclusion of patients with global cartilage damage, that continued to develop during follow-up. They cautioned against operating with pre-existing arthritis. With anteriorisation of the tubercle, Pidorianno et al (1997) found a correlation between pre-existing distal lateral articular damage and patient satisfaction. In 2005 Carney et al found that with this procedure stability was maintained at three and twenty-six years with a small deterioration in knee score. Koeter et al (2007a) followed patients where the procedure had been performed for lateral facet wear or instability and found global improvement in knee scores at two years. Buuk and Fulkerson (2000) followed patients with instability and distal lateral patella lesions and found good to excellent knee scores at eight years. Other authors have supported the use of this operation for maltracking with or without inferolateral cartilage damage (Palmer et al, 2004; Pritsch et al, 2007). The procedure is an effective treatment for instability and with anteriorisation of the tubercle is an effective treatment when inferolateral

patellar arthritis is present. Many surgeons may use this as a “one procedure for all” technique by deliberately over-medialising the tubercle. The procedure may be complicated by early arthritis, non-union, over correction, neurological injury and fracture, and its use should be judicious (Fulkerson, 1999).

#### Trochleoplasty:

Trochleoplasties are a group of procedures that alter the shape of the femoral trochlear to make it more congruent and aid in the stability of the femoral articulation. The indication for surgery remains the presence of a lump in the place of a groove in the trochlear. In patients over the age of thirty the cartilage becomes stiffer and more brittle making flap necrosis more likely. Several different trochleoplasty techniques have been proposed including elevating the lateral condyle (Albee, 1915), a deepening trochleoplasty (Dejour and Saggin, 2010; Mase, 1978; Verdonk et al, 2005; Utting et al, 2008) and a recession trochleoplasty (Goutallier et al, 2002). The lateral elevation trochleoplasty has lost favour as it overloads the lateral condyle and the lateral patella leading to early arthritis. The most utilised technique is the deepening trochleoplasty where the trochlear cartilage is elevated as an osteochondral flap before the underlying bone is reshaped and the flap is taped back down to its new deeper bed. There are several small series published on the results of trochleoplasty that propose the procedure, particularly in conjunction with soft tissue realignment (Schottle et al, 2005; Donell et al, 2006; Koeter et al, 2007a; Utting et al, 2008; Koeter et al, 2007b; McNamara et al, 2015). The cartilage flap survives well and biopsies of the flaps at nine months show healthy cartilage (Mainil-Varlet et al, 2003). The largest patient series with the longest follow-up comes from Eldridge’s series in 2015 185 patients followed for up to 12 years. They concluded that there were significant improvements in the patient reported outcome measures in the medium term and that it remained an effective treatment for patellar instability where indicated. Trochleoplasty remains a procedure with limited applications to be used where normal kinematics can be restored.

#### Medial patellofemoral ligament (MPFL) reconstruction

The MPFL may be damaged as a result of a specific traumatic event, such as a forced tibial external rotation in a valgus knee. When the MPFL is ruptured this results in the patella tilting laterally and subluxing laterally and may result in instability. The literature describes techniques for reconstruction, biomechanical studies discuss the best knee position at which to tighten the graft. There are several studies in the literature that support the effectiveness of the

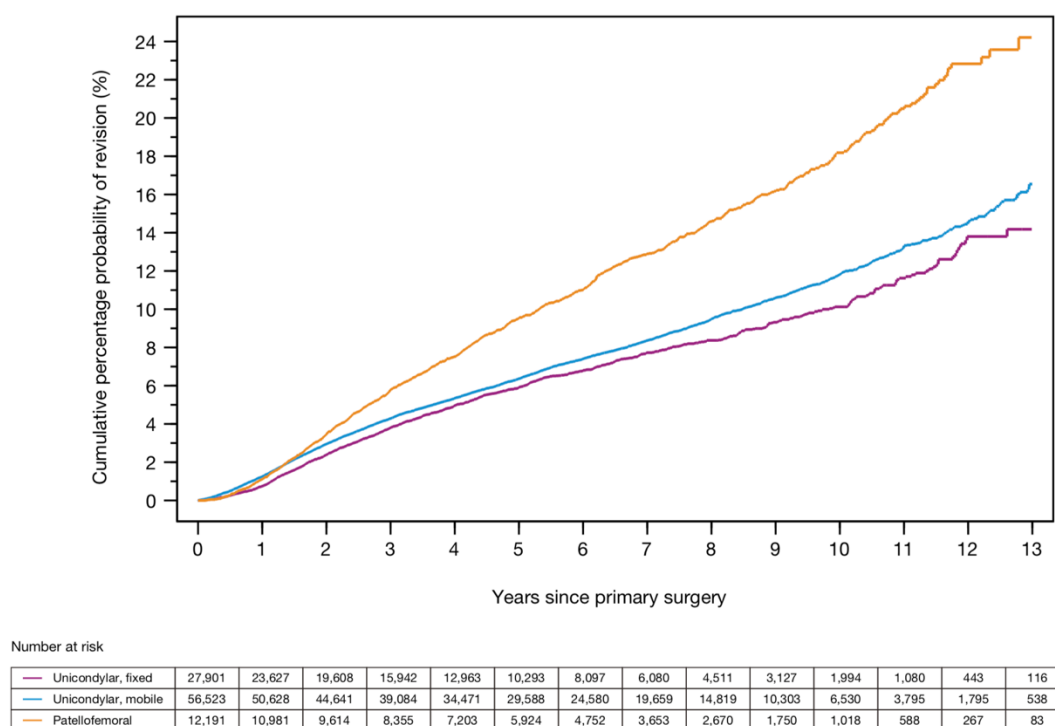
MPFL reconstruction at preventing further dislocation (Panagopoulos et al, 2008; Mikashima et al, 2006; Nomura and Inoue, 2006; Bitar et al, 2012). One systematic review included eight papers (186 MPFL reconstructions) and concluded that MPFL reconstruction provides favourable results (Smith et al, 2007). However the authors draw more conclusions regarding the quality of research available than efficacy of this surgery.

In cases of traumatic dislocation without distal osseous deformity or lower limb malalignment MPFL reconstruction may be an effective treatment. However, if either of these factors is present the operation will over constrain the patella medially leading to stiffness and arthritis. Biomechanical studies have demonstrated the risks associated with over constraining the patella and the resultant damage to the medial patella cartilage (Steiner et al, 2006; Elias and Cosgarea, 2006).

#### Patellofemoral arthroplasty

Where instability has been present for longer significant arthritis may develop. In these cases, realignment and soft tissue procedures are not successful and the only remaining option is arthroplasty. Total knee arthroplasty, although successful at relieving pain in 70-80% of patients, is not a favoured choice in this young age group (Callahan et al, 1994). With careful selection patellofemoral arthroplasty can offer successful pain relief in 80% (Ackroyd et al, 2007). The most common complication with patellofemoral arthroplasty is the development of tibiofemoral disease necessitating revision. The procedure is less common than other forms of knee arthroplasty accounting for 1.2% of the total number of arthroplasty procedures performed. The national joint registry is the largest joint registry in the world. This describes a high rate of revision surgery amongst these patients. The Kaplan-Meier curve from the 14<sup>th</sup> NJR report is included below.

(c) Unicondylar and patellofemoral partial knee replacements



© National Joint Registry 2017

Figure 10. Kaplan-Meier survival curve for patella-femoral replacements and other partial knee replacements.

Different aetiologies, different treatments.

There are disadvantages to using just one operation to address all patella instabilities. As the treatments for instability first developed this was often at the cost of cartilage. As discussed previously, Arnbjornsson et al (1992) performed a retrospective study of patients who had bilateral patellar instability and had received surgery on one side only. Twenty-one patients were followed at 14 years and it was found that 75% of joints treated developed arthritis compared to just 29% of those untreated. The study does not account for selection bias. Similarly, Crosby and Insall (1976) demonstrated that 65% developed arthritis if treated for instability with surgery but just 4% if untreated.

An MPFL reconstruction performed when the problem arises from trochlear dysplasia or distal tibial tuberosity anatomy will result in overloading the trochlear cartilage and the development of early arthritis (Elias and Cosgarea, 2006; Steiner et al, 2006). Hopper et al (2014) reported the clinical, functional and radiological outcomes of 72 knees undergoing MPFL reconstruction and sought to correlate the presence of several variable to outcomes. They noted poor outcomes in the presence of post-operative patella fracture, erroneous tunnel placement and trochlea dysplasia, they noted poor outcomes with lower patient satisfaction amongst those with severe trochlea dysplasia. Of the seven patients who had severe trochlea

dysplasia (Dejour grade C/D) all sustained a further dislocation. An isolated lateral release with medial plication has only short term benefits (Lattermann et al, 2006). Trochleoplasty will not successfully correct the instability unless the overall alignment is addressed (von Knoch et al, 2006). An approach tailored to correcting the anatomical pathology is increasingly favoured (Colvin and West, 2008; Andrish, 2008).

The pathoanatomy specific approach deals with each problem individually with the objective of restoring normal anatomy, kinematics and function. The tibial tuberosity transfer can deal with abnormal tuberosity anatomy, an MPFL reconstruction with a ruptured MPFL, trochleoplasty with a convex trochlear groove and arthroplasty with arthritis. These can be performed in conjunction with a medial plication and lateral release.

A Cochrane review of surgical and non-Surgical interventions for treating patellar dislocation pooled to findings of five randomised studies and a quasi-randomised study (Smith et al, 2015). Although they found weak evidence to support the use of surgery their main conclusions relate to the paucity of evidence. They quote the need for adequately powered large randomised controlled studies and the need for recording adverse events and long term outcomes.

## Summary of introduction

The literature reviewed in the introduction leads to the following observations:

- The patellofemoral joint is one of the most loaded joints and is one of the least stable joints.
- Radiological patellofemoral arthritis is more common than symptomatic patellofemoral arthritis.
- Biomechanical abnormalities may lead to cartilage abnormalities that are a precursor to arthritis.
- The unstable joint might have a different pattern of congruence to the stable joint.

These observations lead me to question whether the anatomical risk factors for patellar instability also play a role in generating symptomatic arthritis. In the following chapter, we explore this further with a case controlled study.

## **Chapter 1b. Patellar instability and symptomatic osteoarthritis of the patellofemoral joint: A case controlled study.**

Several study designs could have been used to answer this question. This section examines the strengths and weaknesses of each technique and explains the rationale for choosing a case controlled study. Randomisation is the most effective way to deal with both bias and confounders. The problem with randomisation for this study question is that it would require that the investigator intervene and generate patellar instability or an anatomic abnormality. This scenario cannot be reconciled ethically and is impractical. Randomisation could be used in a biological simulation in a laboratory with a model or cadaver. Just such a study was performed by Belleman's team, and they found an association between patella alta and abnormal cartilage pressures (Luyckx et al, 2009). However, uncertainty remains as to how this model translates in vivo over a period of several years. Adaptations of gait and activity level may take place and the outcomes remain uncertain.

A prospective longitudinal study could evaluate this question. A well-resourced study of this type was attempted by The Multi Centre Osteoarthritis Study (Stefanik et al, 2010). They performed a longitudinal study where patella height was measured using the Insall-Salvati ratio (ISR) on the baseline lateral radiograph and cartilage damage was graded on MRI at baseline and at 30 months in the patellofemoral joint. They examined the association of the ISR with the prevalence and worsening of cartilage damage. The major flaw with that study is that it cannot be generalised to clinical practice as the correlation between arthritis and symptoms in the patellofemoral joint is poor. For a longitudinal study to be generalisable for this problem it would require that follow-up take place up until severe and symptomatic arthritis was identifiable. This would require a very large baseline population and a prolonged follow-up.

A case controlled methodology has several weaknesses and strengths, which are discussed below. There is a unique opportunity in Bristol as the city has been a centre for the treatment of patellar instability and arthritis since the 1980's. The Bristol Knee Arthroplasty database contains 665 cases of patellofemoral arthroplasty and represents a significant resource. Patients treated in the last eight years also have radiographic imaging available that was used during pre-operative planning (after eight years the radiographs are destroyed). There is also an ethical burden to ensure that the resources of the database are fully utilised. The literature review and clinical understanding arising from clinical practice underpin the choice

of methodology. Although a case controlled study is considered to be the highest order of evidence it will permit us to achieve most robust answer possible with our current resources.

### **Considerations when designing a case controlled study**

In *Modern Epidemiology* (1986) Rothman summarises the challenge of designing and interpreting a case control study. “because it need not be extremely expensive nor time-consuming to conduct a case-control study, many studies have been conducted by would be investigators who lack even a rudimentary appreciation for epidemiologic principles. Occasionally such haphazard research can produce fruitful or even extremely important results, but often the results are wrong because basic research principles have been violated” . They are easily performed but often of limited value due to confounding variables or the introduction of bias. The critics of case-controlled studies need only look at history for a retort. John Snow may have performed the first case controlled study in 1855 when he traced a cholera epidemic back to the Broad Street water pump; noting that the workers at the brewery seemed to be immune to the disease; they drank only the fermented beer and no water from the Broad Street pump. Shortly afterwards Reed used a similar methodology with yellow fever (Reed et al, 1900). Janet Lane-Claypon brought the technique into medical practice identifying the association between low fertility and breast cancer in 1926. In 1950 four case control studies demonstrated the association between cigarette smoking and lung cancer, most famously the British Doctor Study (Doll and Hill, 1950).

Both the strength and the weakness of case-controlled studies are in their directionality. They are always retrospective and as such it is sometimes referred to as “research in reverse” (Schulz and Grimes, 2002). This retrospective element permits utilisation of all known cases so it becomes a realistic technique for studying rare or emerging diseases, or those where the induction period makes follow-up prohibitive. This design will be well suited to the goals of this study.

The validity of case controlled studies may be threatened by bias, confounding or chance. As the results of the study present the contrast of the exposure to the cases and the controls the validity can be troubled as much by problems in the control group as the case group. Cases and controls may be identified from a cross-section of the population at a given time or from incident cases. The risk of including the prevalent and incident cases is that the diagnostic criteria may change over time and introduce bias. Cases typically represent a sample of the population with the disease, and as such may be representative of that population. This representativeness that study groups have of a population may be challenged by patient self-



selection. An example of self-selection in this study group would be that patients who have a dislocation may be more likely to seek arthroplasty when their knee cap eventually becomes arthritic, even if the two events are not connected.

We are fortunate to have a population of patients who have undergone surgery for the precise outcome in which we are interested. These patients have all developed the outcome, but how many subjects are exposed to a specific postulated risk factor or factors without developing the outcome is unknown. The problems that may arise at this stage are in the definition of the outcome; this will later feed into the generalisability of the study and its external validity. Here we may examine the example of John Snow's Broad Street pump study as he could have looked at those who had died of cholera rather than the overall number of cases. This would have introduced a bias excluding survivors of the disease. His objective however was not to find out what the cause of mortality was but where the disease originated from; if he had excluded survivors, this would have reduced the overall numbers and reduced the power of the study. More importantly it would have produced a bias in favour of confounders associated with likelihood of death. In our study we wish to ascertain if patellar instability leads to severe arthritis, so unlike Snow we wish to include only the very severe cases to achieve representation of the symptomatic population.

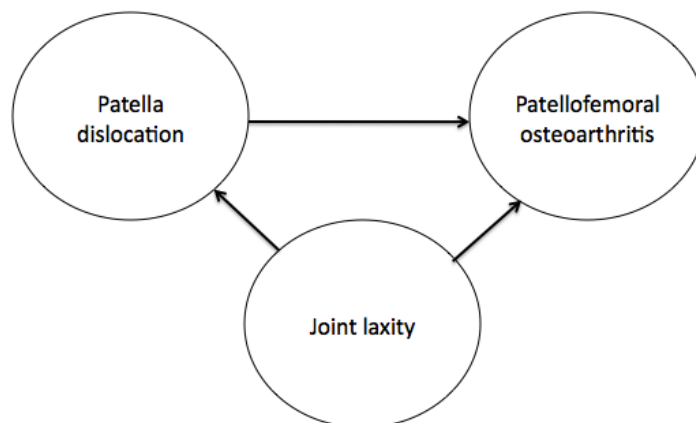
For this study, the ideal case is a joint that is healthy with the exception of the patellofemoral compartment. The cases need to be sufficiently severe that the subject wishes to undergo treatment and that it is recommended by the treating clinician. These requirements lead the investigator to patients who have undergone patellofemoral arthroplasty surgery. To qualify for this surgery the patient must have a severely degenerative patellofemoral compartment, be free of arthritis in the tibiofemoral compartment and be free of inflammatory and septic arthritis.

The challenge of case-controlled studies is in attempting to eliminate bias and confounding factors. Case-controlled studies begin not with the exposure of a study group but with an outcome in a case. Cases and controls are grouped and the exposure or exposures of this group are measured and compared to the exposures of a group without the outcome. The exposure rates are then compared between the two groups and the odds ratio is calculated. Where a multivariate analysis is used, the relative importance of different risk factors can be weighed. The methodology does not permit the measurement of incidence.

In cases-controlled studies internal validity can be challenged by recall bias, misclassification of exposure or from confounding variables. Recall bias is particularly problematic where the subject's memory is relied upon and may be subject to the effect of the

outcome. The development of the disease state may act to alter or even sharpen the subject's memory, whereas the control group may have forgotten the exposure if the case group have already themselves attributed the exposure to the outcome they may have replayed the memory in conversation or their internal dialogue. Roese et al (2012) also refer to hindsight bias or the "knew it all along" phenomenon which is composed of memory distortion, incorrect belief about likelihoods and beliefs in one's own predictive abilities. This complex area has been the subject of several studies that have attempted to quantify the effect. The effect of recall bias may be overstated, numerous studies have failed to show a large impact from recall bias (Stepan et al, 2013; Gefeller, 2009).

A confounding variable is one where the variable is associated with both the exposure and the outcome without being on the pathway of causation. Where confounding variables are recognised attempts can be made to minimise and measure their effect, an understanding of these may caveat the study results. Bias is minimised either by attempting to compensate for it through matching, by later exclusion thorough statistical manipulations such as the Mantel-Haenszel technique or by inclusion of that factor in a logistic regression.



**Figure 11. Joint laxity is one example of a potential confounder. Image demonstrates the potential confounder relationship from patellar instability to arthritis.**

### Missing data

Various techniques can be used to address the challenge of missing data. The simplest method is the complete-case analysis where only complete data sets are included in the analysis. This is something of a default technique, as statistical packages will automatically exclude cases with incomplete data from a logistic regression. Some authors propose this to be the only technique that does not introduce bias (Miettinen, 1985). It is worth noting that although the method does avoid introducing a new bias, it also fails to address any existing

bias. The major disadvantage of this technique is its inefficiency; large numbers of cases can be lost due to incomplete data. In self-filled surveys this is particularly problematic as patients frequently skip questions. Another technique is the missing value indicator technique, where missing values are replaced with a 1; the technique is biased under most conditions (Vach and Blettner, 1991). Another commonly used technique is to impute a mean value into the missing datum space; although this is a much more efficient technique it artificially narrows the variance, multiple data points having precisely the same value (Greenland and Finkle, 1995).

There are three further categories of more sophisticated techniques (Greenland and Finkle, 1995). Multiple imputation methods involve creating multiple copies of the data and replacing missing values with randomly generated figures. Then the various datasets are analysed and combined, taking account of imputation variability. Maximum likelihood and maximum pseudo-likelihood methods create a model to fit the dependent variable, co-variable and missing figures. There are also weighted estimating equation methods. As with maximum likelihood, a model is created but in this scenario the outcome is used to weight the regression.

### **Research subjects**

For the study to be generalisable to those people with debilitating patellofemoral arthritis, the outcome that characterises a case needs to be severe symptomatic patellofemoral arthritis. The ideal case would have developed severe patellofemoral arthritis, sufficiently severe for them to wish for surgery.

The study could have attempted to find new cases of patellofemoral arthritis as they arose, before undergoing surgery. This would be a long process entailing considerable resources; not all cases go on to surgery, so non-operative cases would not all be identified. The indication for a patellofemoral replacement is that the patient has arthritis isolated to the patellofemoral joint and is free of inflammatory arthritis, tri-compartment arthritis, post-traumatic arthritis, septic arthritis and inflammatory arthropathies. These indications are consistent with the ideal case selection and there exists a large pool of these patients. The demographic details and treatment history have already been documented in an established arthroplasty database. They form an appropriate case group that can be generalised to apply to patients receiving arthroplasty.

### **Definition of controls**

For a control group to be relevant it must have been at risk of developing the outcome but has not developed it. For example, if a study evaluates the effect of an exposure on prostate cancer rates then the controls must all be men. The selection of the control group offers an

opportunity to address confounding variables. Confounding variables were identified in our literature review and are those variables that are associated with both the outcome and the exposure without being on the causal pathway.

Risk factor	Associated with patellar instability	Associated with patellofemoral arthritis.
Female sex	Yes	Yes
Joint hyperlaxity	Yes	Yes
Elevated body mass index	No	Yes
Age	Yes (inverse)	Yes
Adolescent patellofemoral pain	Yes	Yes
Previous surgery	Yes	Yes

**Table 4. Potential patellar instability and arthritis confounders considered in table.**

A control group must be comparable to the study group, at risk of the disease and resemble the cases as far as possible. Where cases go through an ascertainment process, then controls must also go through this process.

The control group selected in this study is composed of those patients undergoing partial knee replacement other than the patellofemoral joint. These patient, undergo a similar ascertainment to patellofemoral patients, they must be healthy enough to undergo surgery, they must live within the catchment area of the hospital and have similar access to healthcare facilities.

One major advantage of this control group is that they will have undergone a similar experience to those having the patellofemoral replacement and by using them we match for recall bias. They are in many respects very similar to the case group other than the location of the resulting pathology and potentially with a different exposure profile.

In this study, the control group is composed of patients who have experienced severe and symptomatic medial uni-compartmental knee arthritis. The remaining knee (patellofemoral and lateral compartment) must be free of arthritis. The controls must have undergone medial uni-compartmental knee replacement. The definition of severe arthritis is again confirmed by radiological imaging of “bone on bone” arthritis and by the patients and clinician’s decision to treat with partial knee replacement.

### Plan for statistical analysis

Matching is a potent method for control of confounders. The initially plan was for matching the age and sex from the smaller patellofemoral database to the larger medial unicompartmental database. It quickly became clear that a large portion of the patients would remain unmatched as the response rate from the questionnaire was not high. It was therefore decided to use a multivariate analysis methodology. This permits that unmatched data be included as a co-variable and that it is weighed in the final odds ratio.

There are various forms of multivariate analysis, and the most common is the step wise forward conditional form in which each co-variable is repeatedly entered in different combinations and the effect of each is measured. This technique is most useful where the model is attempting to predict a dependent variable on a continuous scale. In this study, the model is attempting to measure a dichotomous variable and, as such, a binary logistic regression was utilised. Binary logistic regression utilises the “enter” technique whereby the statistics are presented for each variable as if they were the last one entered in the model. The familiar step wise modelling is not presented here.

There are two contrasting methods of deciding which items should be included in a multivariate analysis (Bursac et al, 2008). The traditional method is to include all available data, the more recent vogue is for “purposeful selection” of data to reduce the number of co-variables to a manageable number of variables. This method has advantages in studies with incomplete data sets. As the number of variables are reduced the number of non-overlapping missing data points are also reduced. This permits a greater number of cases to be included, saving cases from being excluded due to missing data in a potentially unimportant co-variable.

Whilst wanting to include all variables, so that no important variable is omitted, it is important to consider that multivariate models can be unstable as a result of multi-collinearity. This phenomenon has been referred to as the “quiet scandal” of statistics by the eminent statisticians of our time (Breiman, 1992). The benefit of logistic regression is that the model identifies overlapping effects and compensates for them. The problem arises when two variables are inputted which ask a similar question. As the model will identify the overlapping effect and suppress the effect of one or both of them. Multi-collinearity may be identified before a logistic regression is performed. In linear regression, it may be identified through a variance inflation factor test (VIF), but this technique cannot be applied in binary logistic regression. One approach is to identify collinearity through correlation of co-variables before testing. This may then be addressed by using only the variable in the cluster most strongly

associated with the dependent variable or by averaging the cluster. An alternative technique is to re-test each time excluding one variable to observe for the effect of multi-collinearity.

Purposeful selection can be used to address the problem of “multicollinearity”. Where two co-variables measure the same outcome they will share the effect in the final model and therefore both will be under reported. By assessing which variables are strongly associated with one another, a decision can be made as to which should be excluded. The following section presents a multivariate analysis with binary logistic regression with a structured purposeful selection of co-variables.

## Hypothesis

Patellar instability is associated with symptomatic degenerative joint disease of the patella.

## Methods:

### Study population & site:

The study was conducted in Bristol, United Kingdom. It was a single centre study. This location offered an advantage to the investigator as more patellofemoral arthritis is identified and treated in this region than anywhere else in the world. This is not a reflection of population differences, but of the local surgical interest in the treatment of the condition. The study utilised the Bristol Knee Arthroplasty database situated at the Avon Orthopaedic Centre, Southmead Hospital, Bristol, UK. The study was a retrospective analysis of prospectively collected data and covered dates between 2002 and 2012.

### Database

The Bristol Knee Database at the Avon Orthopaedic Centre was used to identify potential cases, those who had undergone patellofemoral and medial unicompartmental knee replacement. This database was initiated in 1976 and is ongoing. All knee arthroplasty surgery performed at this centre has been included since this date. The database holds over 10,000 arthroplasty episodes, non-operative cases are not recorded in the database. The database holds patient reported outcome measures for each operation type as well as demographic information. Patients are followed up at standard time points of 1, 2, 5, 8, 10, 12, 15, 18, 20, 22, 25, 28, 30, 32 and 35 years. Body mass, laterality and age were collected.

### Definition of cases and controls:

A multivariate analysis using binary logistic regression was planned and executed. The subject and control inclusion and exclusion criteria are summarised below.

Inclusion criteria for the cases:

- History of severe osteoarthritis of the patellofemoral joint.
- Patients with partial knee arthroplasty (patellofemoral).
- Patients who are more than 2 years since surgery but less than 10 years since surgery.

Inclusion criteria for controls:

- History of severe osteoarthritis of the medial compartment of the knee.
- Patients with partial knee arthroplasty (medial compartment).
- Patients who are more than 2 years since surgery but less than 10 years since surgery.

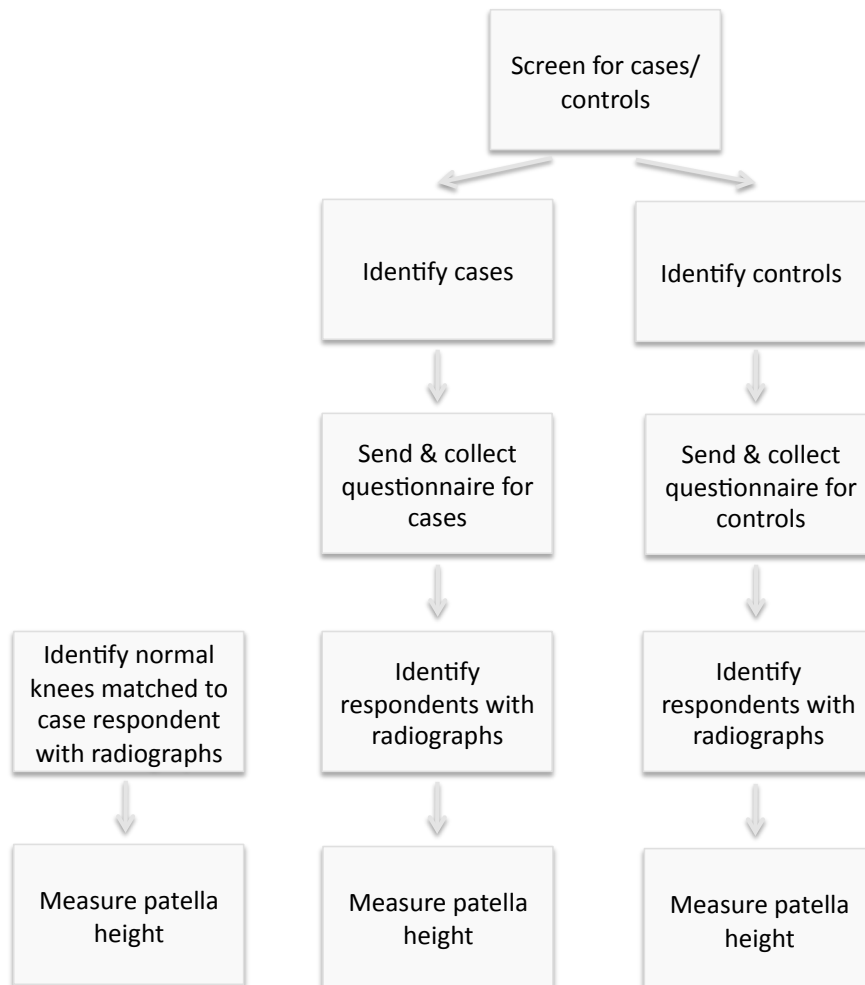
Exclusion criteria were determined on the basis of those factors that would make the inclusion in the study unsafe or where obvious causes of generalised knee arthritis were identified. As identified In the literature review the following factors are considered generalised arthritis risk factors; knee trauma, knee sepsis, inflammatory arthropathy. Obesity was considered as an exclusion criteria but as the data available was incomplete it was decided not to include this, discussed in later section. Revision surgery was excluded as a risk factor as the healthcare experiences of these patients relating to their knee, thereby impacting the “recall bias” Roese et al (2012).

- For cases: Severe arthritis of the knee outside of the patellofemoral joint.
- For controls: Severe arthritis of the knee in the patellofemoral joint.
- History of major knee trauma.
- History of revision surgery following the partial knee arthroplasty.
- History of knee sepsis.
- History of inflammatory arthritis.
- Age less than 18 years.
- Patient lacks capacity to consent.

### **Data Collection**

Data were collected from the Bristol Knee Database, by postal questionnaire and from medical imaging. The flow diagram details the order in which data were collected and the questionnaire and other data collection methods are detailed below.





**Figure 12. Recruitment plan flowchart.** Left most column is for matched controls to establish baseline normal patella height. The middle column is for the cases (patellofemoral cases) and the right for controls (medial unicompartment cases).

### Exposure measure of patellar instability and other variables

#### Questionnaire

A literature review at the outset of the study (2012) revealed no validated questionnaire focusing on patella instability. Since then the Norwich group have developed a validated questionnaire that has the aim of assessing severity of patella instability (Smith et al, 2014). This was not available at the time that this study was designed. However the Norwich questionnaire is designed to discuss the patients recent symptoms rather than those from many years previously. If it had been available at that time it would have formed part of but not the entirety of our questionnaire.

A self-filled postal questionnaire was designed to elicit any contact with the exposure of patella dislocation. When designing the questionnaire, consideration was made to minimise exposure to misclassification. The challenge with eliciting a history of patellar instability is

that a spectrum of disease exists between mild instability and severe instability (of which dislocation is a feature). The patient cannot directly observe instability unless it results in a dislocation.

Patients with patellar instability may feel their patella or their knee to be giving way, but equally this history may be consistent with other knee pathologies such as an anterior cruciate ligament injury, meniscal tear or loose body.

Patients who fulfilled the inclusion criteria and who had not been followed up within the past year were identified from the Bristol Knee Database. The standard follow-up questionnaires were sent to the patients including International Knee Documentation Committee (IKDC) score, Oxford Knee Score and Western Ontario and McMaster Universities Arthritis Index (WOMAC). In addition to these questionnaires, the study questionnaire was stapled to the final page. The self-filled postal questionnaire was sent to the patient with a prepaid self-addressed envelope in order to maximise response rate.

The package was sent via second class post, and to increase the response rate a self-addressed prepaid envelope was included within the package. A three-month cut off was set; after this date no further questionnaires would be included. No attempt was made to send further post or phone calls to the non-respondents.

Responses were recorded by on a spreadsheet. In some cases, questions were not answered, left blank by participants. These answers were counted as neither yes or no and the case was removed from the logistic regression. The only exception was in the case of the question on the “feeling of instability”. If the patient had answered yes to the question “Did your knee cap ever dislocate” then the feeling of instability question would be marked as positive. This was the case in five patients.

Some patients have unstable knee caps that can dislocate.

We would be grateful if you answer some questions about your kneecap **before** you had the replacement surgery:

1. How old were you when you knee cap first became painful?
2. Did you knee cap ever feel unstable/unreliable/like it might give way?  
Yes/No   
How old were you when you knee cap became unstable?
3. Did your knee cap ever dislocate?  
Yes/No   
How old were you when your knee cap first dislocated?
4. Did the knee cap ever feel unstable when walking?  
Yes / No
5. Did the knee cap ever feel unstable on the stairs?  
Yes / No
6. Did the knee cap ever feel unstable when playing sports?  
Yes / No
7. Before the joint replacement surgery did you have any surgery on your knee cap? Yes / No

**Figure 13. Postal questionnaire, sent to patients in the case-controlled study.**

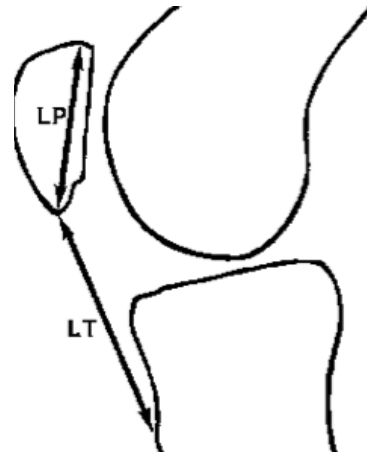
## Imaging

In every patient where a questionnaire was received a search was made of the picture archiving and communication system (PACS) at North Bristol NHS Trust and University Bristol Healthcare Trust. The PACS systems hold images that date back to its inception in 2004. Imaging was evaluated on the “Insignia” computerised PACS which includes a digital calliper. The digital calliper is calibrated when used on MRI imaging but does not take into account the 10% magnification which typically takes place in radiographic imaging. Where searches were not fruitful, a second search was made of the old radiograph depository by hand.

Images were considered adequate if:

- A pre-operative lateral radiograph was available.
- The knee was positioned at between 10 and 30 degrees of flexion.
- Satisfactorily rotated with adequate overlapping of the femoral condyles.

The images were used to measure patella height utilising the Insall-Salvati ratio. The maximum length of the patella (LP) was measured and the length of the patella tendon (LT) was measured. Using these measures the Insall-Salvati Ratio (ISR) ratio was assessed by dividing LT/LP. The measurements were made by myself in the first instance and where inter-observer measurements are reported these are made by my assistant (HC).



**Figure 14. Insall-Salvati ratio. Image from de Carvalho et al 1985. The maximum length of the patella (LP) is measured and the length of the patella tendon (LT) are measured.**

The ISR measurement is a ratio. Ratio data are known to create exaggerated odds ratios if utilised in multivariate analyses. In order to include the ISR in the multivariate analysis, the data would need to be converted from continuous ratio data to ordinal data. For this reason, a reference range was created for the ISR from a “near to normal” population.

#### Defining a reference range for ISR

Although it is desirable to use a universally recognised reference range where possible, there were two problems with the ranges described in the literature. The absence of a universally accepted range in the literature was a concern; the threshold for patella baja has been described between 0.74 and 0.8 where for patella alta this has been defined as 1.2 or 1.5 (Shabshin et al, 2004; Grelsamer and Meadows, 1992). The other concern was that little attention is given to data partitions, there are no data describing similarities or differences between age ranges or sex amongst adults. These concerns prompted the development of a reference range for this study. The Clinical and laboratory Standards institute (CLSI) provide guidance in their publication “EP28-A3C Defining, Establishing, and Verifying Reference Intervals in the Laboratory; Approved Guideline.”

When defining a reference range, consideration must be given to partitioning the subjects. Typically, this is by age and sex; examples include different haemoglobin reference

ranges for men and women or the different normal range of neutrophils for adults and children. Some authors have found minor sex-related differences in the mean ISR (Shabshin et al, 2004). In this case, the reference range is only intended for this study, so they were matched precisely by age and sex. This was done so that the reference range precisely represents the same partition as the case data.

The CLSI recommends a minimum of 120 observations when establishing a reference range and 20 when validating an existing reference interval. In the recent third edition they also include guidance on producing a reference interval with as few as 20 observations. The hospital PACS system contains more than 100,000 knee radiographs, so it was possible to perform 2:1 matching and attain a reference range with more than 12 subjects. The “near to normal” population was found on the institutional PACS system. The “near to normal” inclusion criteria were:

- The knee was positioned at between 10 and 30 degrees of flexion.
- Image was satisfactorily rotated with adequate overlapping of the femoral condyles.
- No fracture present.
- No knee haemarthrosis or other knee effusion present.
- No arthritis in any compartment.

The PACS software permits searches to be performed by name, hospital number, date of birth, body part, imaging modality (ie radiograph or MRI or CT scan) or date of procedure. For each patient included in the case group two further patients were identified from the PACS system. Searches proceeded as follows:

1. The body part was defined as knee and the modality as plain radiograph.
2. Sex matched to the PFJ patient's.
3. The date of birth of the PFJ patient was entered.
4. Where no suitable match was found on that day searches were made of the day before. If no suitable match was found, then a search was made for the day after. Where no suitable match was found, then a further search was made for two days after. This alternating widening of the field continued until a match was found. In all cases, two matches were found within two months of the date of birth.

### **Data handling and cleaning**

As there is a large body of subjects available for this low cost study. We will use the less efficient complete-case analysis and describe the missing data demographics. We also minimised loss by purposeful selection of co-variables. Data was scanned for outliers and the effect of inclusion/exclusion of those considered on an individual basis- this is detailed In the results section.

Numerous approaches have been described including the use of custom-made statistical software packages In this study a predetermined structured was used to approach to perform shortlisting of variables for the multivariate analysis. This purposeful selection has several advantages. Most importantly, it permits the number of overall co-variables to be reduced; where there are missing data in different co-variable this permits an overall increase in the number of cases as there are no exclusions from missing data in potentially irrelevant co-variable categories.

### **Sample size and power**

The sample size defined by the full available population regardless an a-priori power calculation was performed. Accepting that there are no equivalent studies on the literature I estimated a medium to small or medium effect of exposure on outcome. An a-priori power calculation indicates that a sample of  $n=80$  will provide at least 60% power for detecting a small or medium correlation ( $r=0.4$ ) and will provide in excess of 96% power for detecting a large correlation ( $r=0.5$ ) between pre, intra and post measures using Pearson's correlation coefficient. Power calculation performed using G-Power (Faul et al, 2007)

## Results

### Case Inclusions

A total of 10883 procedures in 8036 patients were available on the knee database at the time of the study. Of those 665 cases of patellofemoral replacement were identified, 475 had taken part in recent follow-up as per standard time points so were excluded. The remaining 190 were sent a questionnaire; in two cases the patient had deceased, 77 did not reply and no explanation was given. Of the remaining 111, cases 38 had plain radiographic imaging that was either inadequate or could not be found on the PACS system. The cases are summarised in the flow diagram.

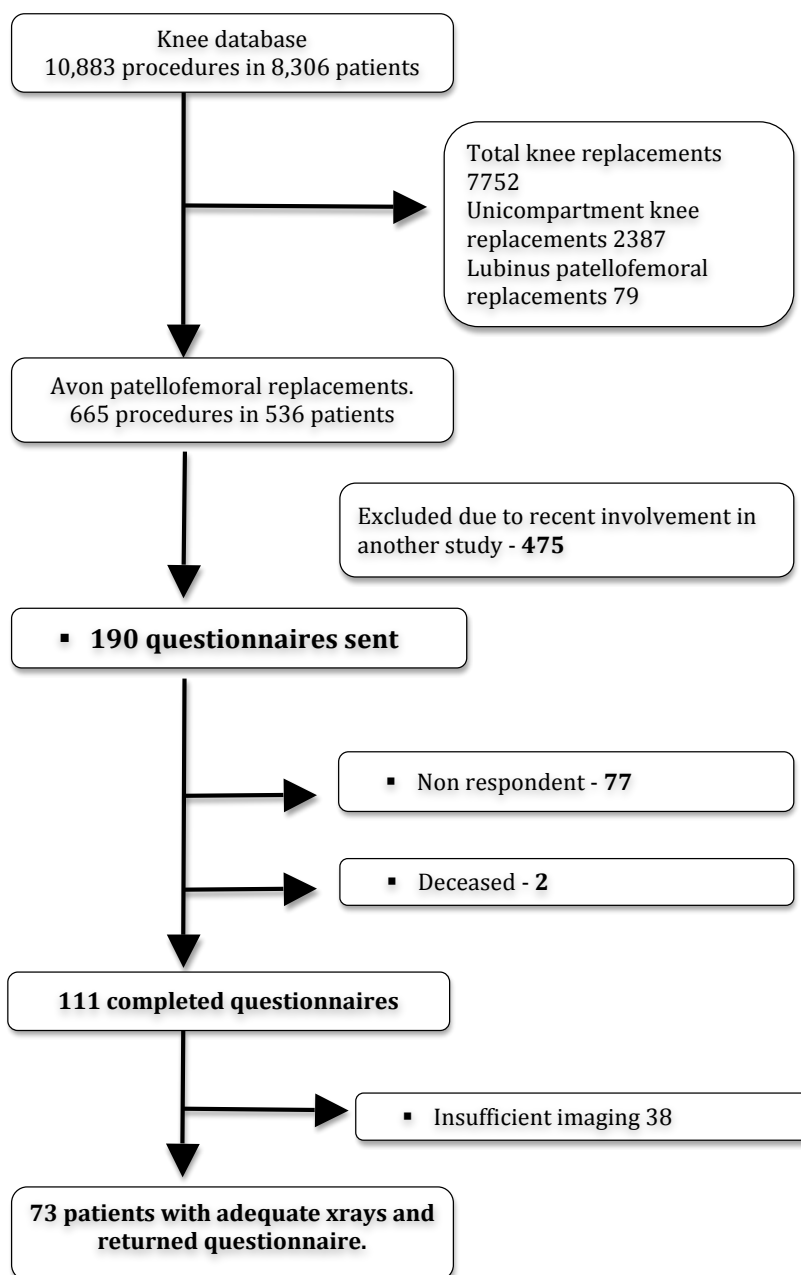


Figure 15. Recruitment flowchart for inclusion/exclusion in case group (patellofemoral arthritis).

### Control inclusions

A total of 10883 procedures in 8036 patients were available on the knee database at the time of the study. Of those, 2387 cases of unicompartmental knee replacement were identified; 1942 had taken part in recent follow-up as per standard time points so were excluded. The remaining 445 were sent a questionnaire; in four cases the patient had deceased, 207 did not reply and no explanation was given. Of the remaining 234 cases, 147 had plain radiographic imaging that was either inadequate or could not be found on the PACS system. The controls are summarised in the flow diagram.

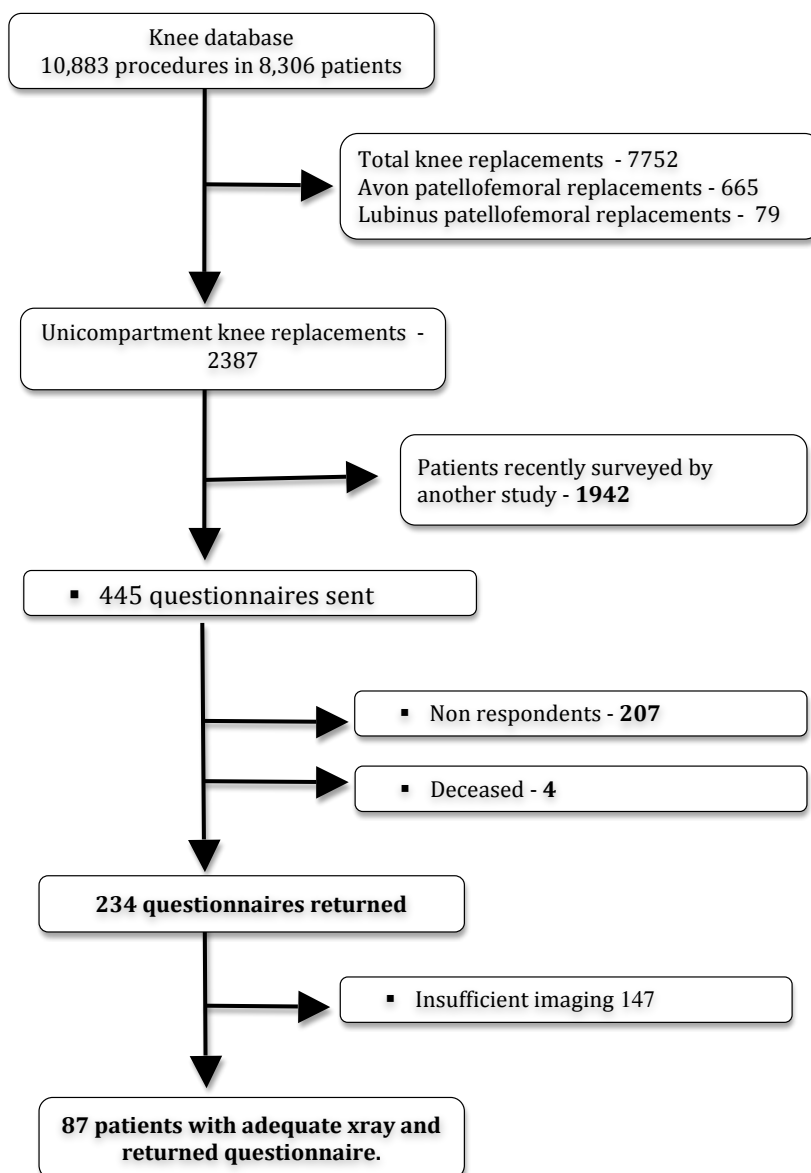


Figure 16. Recruitment flowchart for inclusions/exclusion in control group (medial arthritis).



## Missing data

Body mass, laterality and age were collected from pre-existing data on the Bristol Knee database. Whereas 100% of the “age at surgery” and “laterality” data were available, the body mass data were poorly recorded. Only 51% (57%) of the patellofemoral and 52% (100) of the medial arthritis patients had complete body mass data.

Rate of return of the questionnaire was 58% (111/190) for the patellofemoral cases and (234/445) 52% for the medial arthritis controls. Presence of returned questionnaire and satisfactory radiographs was 37% (72/190) for the patellofemoral cases and 20% (87/445) for the medial arthritis controls. The age and sex characteristics of each of these is presented in the table below.

Condition	Age in years at surgery.	Sex	N
Cases (PFJ) all surveyed.	mean 56.3 SD 0.73	73% female	190
Controls (medial) all surveyed.	mean 67.1 SD 10.2	51% female	445
Cases returned questionnaire and adequate radiographs.	mean 50.5 SD 11.1	79% female	72
Controls returned questionnaire and adequate radiographs.	mean 70.9 SD 8.8	48% female	87
Cases included in multivariate analysis.	mean 49.1 SD 10.4	77% female	62
Controls included in multivariate analysis.	mean 71.4 SD 8.58	40% female	48

**Table 5. Recruitment rate. The top two rows include all cases that were approached. The middle two rows are those have completed questionnaires returned & radiographs available. The bottom two rows represent the cases where all of the data required for the analysis is included and therefore they are included in the final analysis.**

Comparison, made by a paired sample t-test, of the patient age characteristics at date of surgery was made between those with complete and incomplete data. Normal distribution of the age characteristics was confirmed by testing the total surveyed study population, the PFJ surveyed population and the medial arthritis surveyed population. The distribution of age at surgery was assessed for normality by the Shapiro-Wilk test. In each case the null hypothesis that the distribution was not normally distributed was rejected (sig 0.066, 0.074, 0.077) by the test.

For the patellofemoral cases with database, questionnaire and adequate radiographs the mean age was 50.6; amongst the total PFJ population this was 56.3. The differences were found not to be statistically significant (paired  $t(71) = 1.727$ ,  $p = 0.088$ ). There was variation in the

sex characteristics; of all surveyed PFJ patients, 73% were female, amongst the PFJ patients with database, questionnaire and radiographs 79% were female.

Comparison of the age characteristics at surgery of the patients with database, questionnaire and radiographic data and the entire medial unicompartmental arthritis survey population was made by a paired sample t-test. For the unicompartmental cases with database, questionnaire and radiographs the mean age was 70.9 years, whereas amongst all surveyed medial arthritis population this was 67.1 years. The differences were found not to be statistically significant paired  $t(84) = 1.702$ ,  $p = 0.092$ . There was minor variation in the sex characteristics; of all surveyed medial arthritis patients 51% were female, amongst the medial arthritis patients with database, questionnaire and radiographs 48% were female.

### Descriptive statistics of questionnaire and radiographic data

The tables below illustrate the findings of the questionnaire before cases were excluded for inadequate radiographs.

	Cases (PFJ arthritis)					Controls (Medial arthritis)				
	N	Min	Max	Mean	Std. Deviation	N	Min	Max	Mean	Std. Deviation
Age of first pain (years)	106	4	77	33.3	18.7	180	10	87	58.8	13.9
Age at first dislocation (years)	46	5	55	16.3	13.5	8	15	69	52	19.7
Age unstable (years)	92	4	75	32	18.4	110	11	88	58.7	14

Table 6. Descriptive results from the postal questionnaire.

	Postal question #	Cases (PFJ arthritis)		Controls (Medial arthritis)	
		N=	yes	N=	yes
Ever unstable	2,3,4,5 or 6	109	81%	232	63%
Dislocation history	3	109	40%	232	8%
Walking instability	4	109	78%	232	45%
Stair instability	5	109	84%	232	43%
Sport instability	6	109	81%	232	37%
Previous surgery	7	111	54%	232	15%

Table 7. Descriptive results from the postal questionnaire.

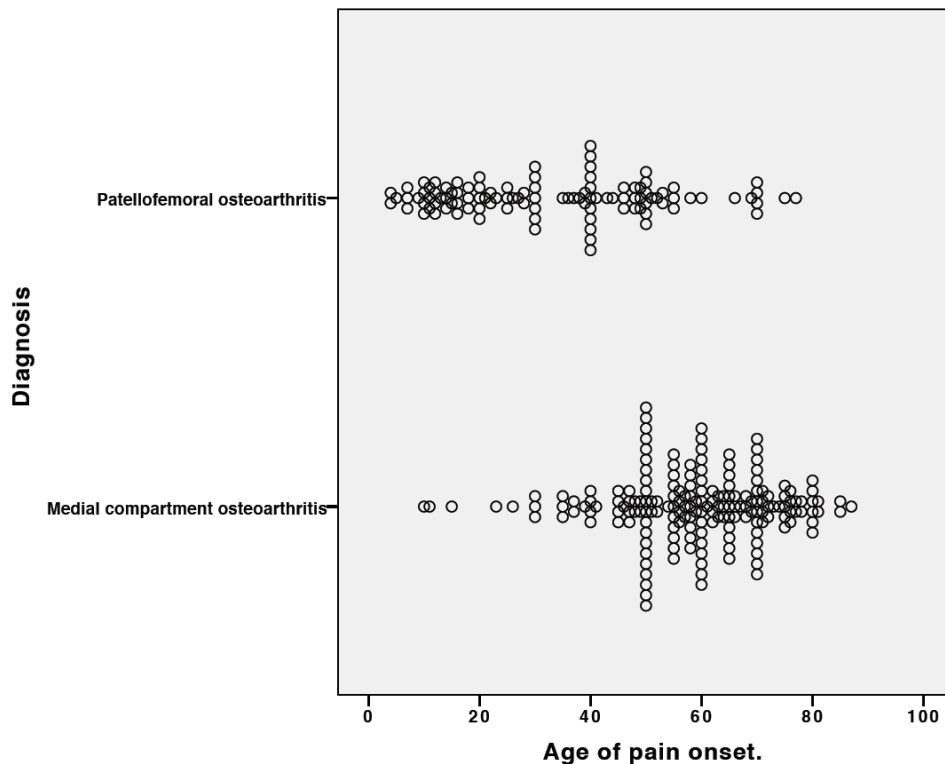
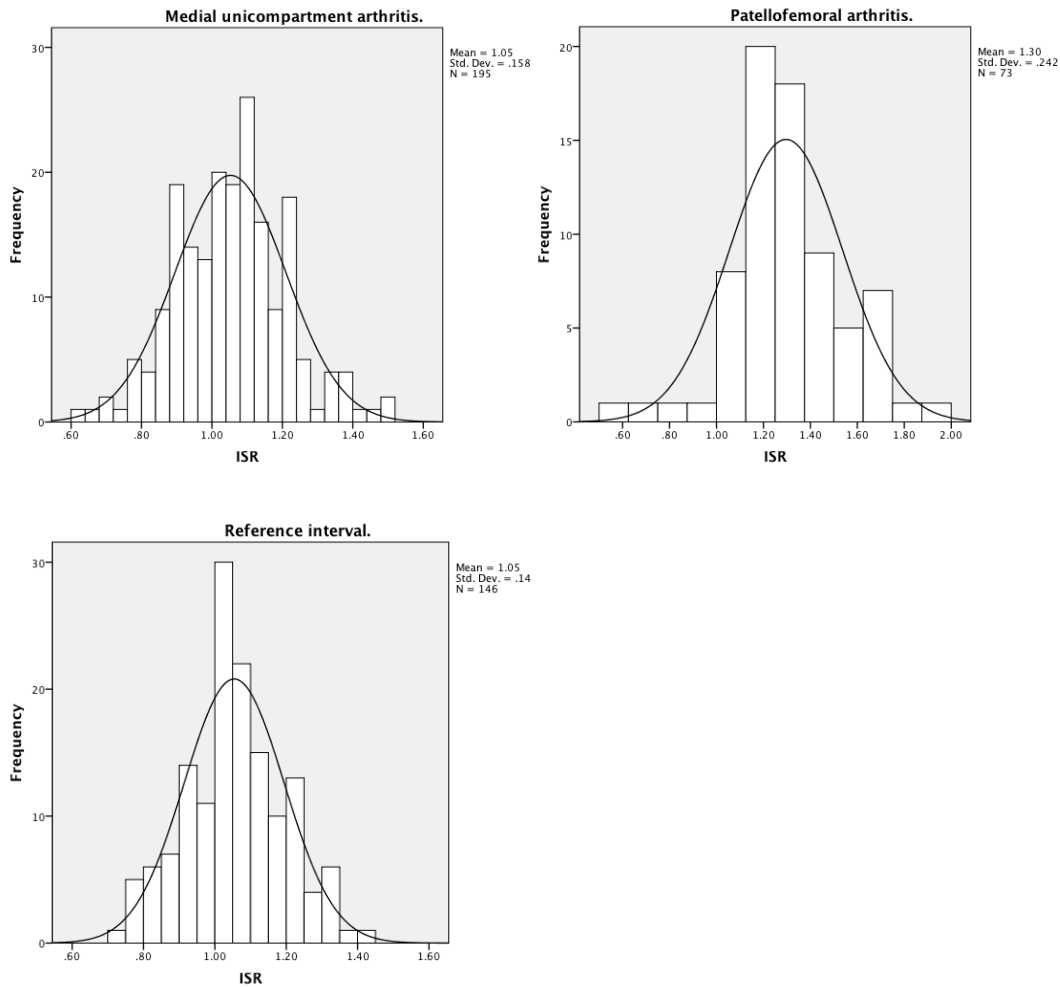


Figure 17. Age of onset of first symptoms experienced by patient. Each dot represents one patient’s response. There is a concentration of responses in adolescence for the patellofemoral cases, first symptoms occurring more commonly after age 40 in the medial arthritis group.

### Descriptive statistics of normal knee “reference range of ISR”

The convention for defining a reference range is to include a range that would include the central 95% of a normally distributed population of non-pathological cases. The 95% is an arbitrary figure as an unknown proportion of these non-pathological cases may eventually develop the disease. The 95% central range relies on the data being normally (or log-normal) distributed. The normality of the data was tested with Shapiro-Wilk test and this rejected the null hypothesis that the data were not normally distributed (see result of Shapiro – Wilk in ANOVA).

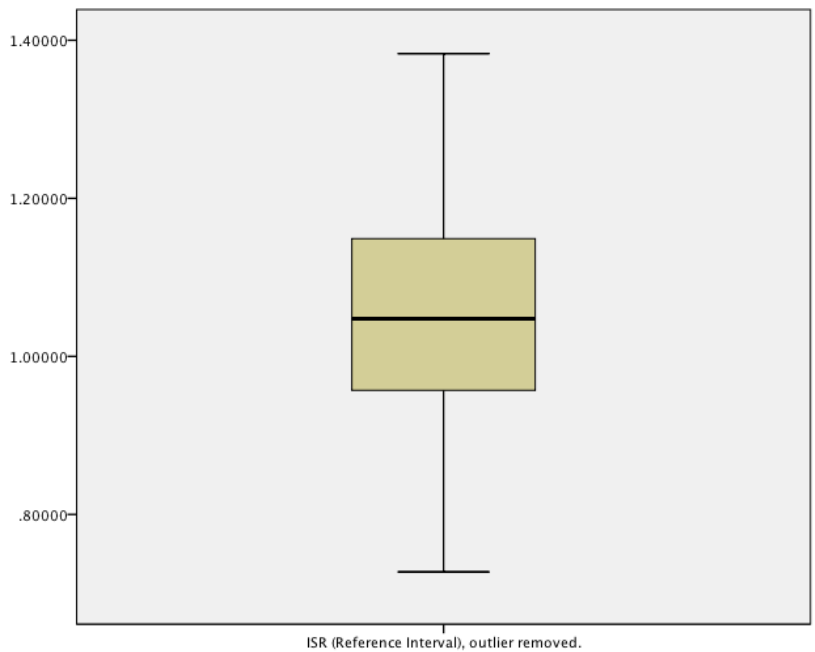
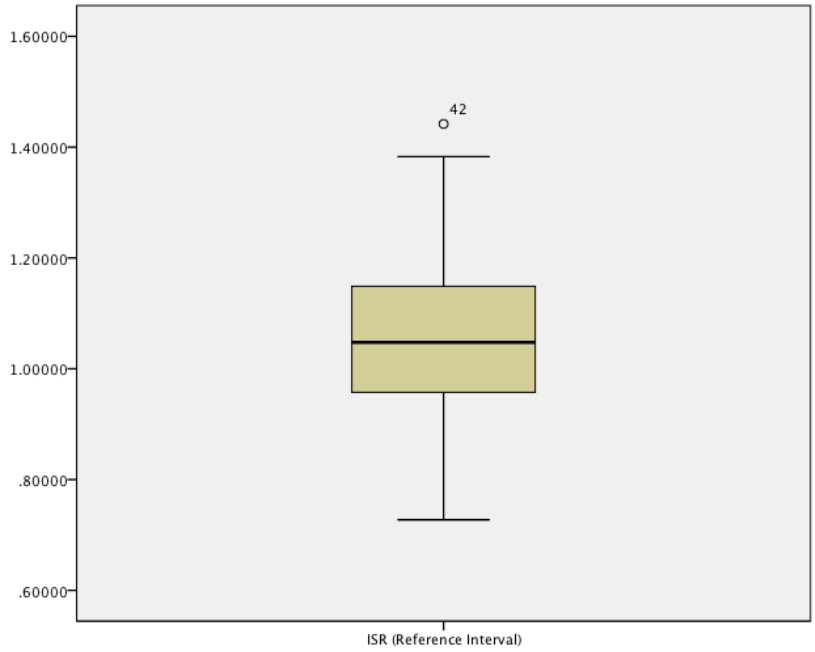
The distribution of patella height measured by ISR was assessed for normality by the Shapiro-Wilk test in the patients with patellofemoral arthritis, those with medial compartment arthritis and those with no knee arthritis. In each case the hypothesis that the distribution was not normally distributed was rejected (sig 0.08, 0.586, 0.717) by the test.



**Figure 18** Histograms of patella height (ISR data) distribution. For medial arthritis (controls), patellofemoral arthritis (cases) and normal knee patients. Each appear to follow a normal distribution but with different central tendency.

### Treatment of outlying observations

One of the recommendations made by the CLSI is that when developing a reference range we should identify and examine outliers, and if they are accurate and significantly impact the variance then consideration to removing them should be made. One outlier was identified, with an ISR of 1.44. The datum point was rechecked and found to be correct. Removing the figure had a negligible effect on the variance changing it from 0.20 to 0.19).



**Figure 19. Box & whisker plot. The significance of the outlier was assessed by visual inspection of the change in appearance of the box plot, this is negligible.**

### Repeatability of measure ISR

The repeatability of the measurements of patella height were assessed by Pearson's correlation coefficient. The measurements were repeated for the primary investigator to give a measure of intra-observer error. All measurements were repeated by another observer for assessment of inter-observer error. Measures were highly correlated for intra-observer error (0.975) and for inter-observer error (0.934).

### Reference range result

The central 95% was selected and the normal range defined as 0.78-1.32.

### Patella alta and patella baja as defined by our reference range

Patella height measured by ISR on a continuous scale was converted to ordinal data.

The ISR was used to classify the patella height as high (alta), normal or low (baja).

	<b>Cases (Patellofemoral arthritis)</b>	<b>n</b>	<b>Controls (Medial arthritis)</b>	<b>n</b>
<b>Patella height classification</b>	ISR<0.78 = 3 (3%) ISR 0.78-1.32 =38 (52%) ISR >1.32 = 32 (43%)	73	ISR<0.78= 4 (3%) ISR 0.78-1.32 = 99 (88%) ISR >1.32 = 10 (9%)	113

**Table 8. Patella height was categorized for each patient according to the reference range from the normal controls. The central 95% from the normal range patients was selected giving a normal range as 0.78-1.32.**

### Results of Binary Logistic regression

As the dependent variable is a dichotomous measure and the co-variables are a mixture of continuous and ordinal data a binary logistic regression was utilized.

Dependent variable: The dependent variable is patellofemoral arthritis or medial compartment arthritis.

Co-variables: The features of the co-variables available for inclusion are included in the table below.

### Purposeful selection of co-variables

A predetermined methodology of purposeful selection was utilised as follows. A correlation table was used to evaluate the correlation of each explanatory variable (see appendix 1). Inclusion was planned according to the following steps:

Step 1. Tests must have a Pearson's coefficient to the dependent variable of greater than .2

Step 2. If the Pearson's correlation is greater than 0.7 between two co-variables then only one with the greatest Pearson's correlation to the dependent variable will be included. In the diagram below each circle contains the co-variable name, the Pearson's co-efficient between the co-variable and the dependent variable and the p value in brackets.

### Application of shortlisting rules

The arrows between the co-variables demonstrate where high multicollinearity (Pearson's co-efficient >0.7) between variable exists.

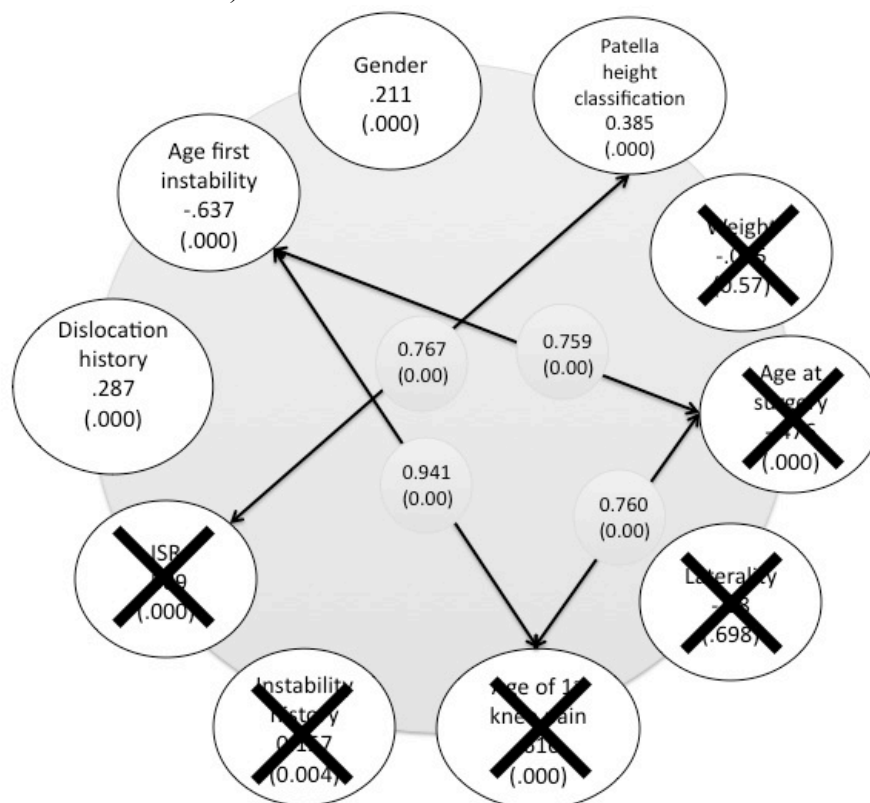


Figure 20. Co-variable exclusions rules applied. The labelled arrows indicate the Pearson's correlation between co-variables that are correlated with the dependent variable.

Co-variable number		Pearsons' coefficient	Sig. (2 tailed)	n	Multicollinearity with co-variable.	Outcome
1	Sex	.211	0.000	539	Nil	Included
2	Laterality	-.018	.698	494	Nil	Excluded
3	Weight	-.035	.573	255	Nil	Excluded
4	Age at surgery	-.476	0.000	531	7,9	Included
5	Patella height classification	.385	0.000	267	6	Included
6	Insall Salvati Ratio	.509	0.000	268	5	Excluded
7	Age of first Knee pain	-.616	0.000	286	4,9	Excluded
8	Instability	.157	.004	341	Nil	Excluded
9	Age of first instability	-.637	0.000	202	4,7	Excluded
10	Dislocation history	.287	0.000	341	Nil	Included

Table 9. Summary of included co-variables. Those co-variable that are “struck-through” are rejected by application of the shortlisting rules.

The variables selected by the shortlisting included sex, dislocation history, age at surgery, patella height classification.

### Logistical regression results

Multivariate analysis was performed with the binary logistic regression function in SPSS (IBM SPSS Statistics for mac, version 23. IBM Corp., Armonk, N.Y., USA). The “Enter Method” was used, including the co-variables identified in the shortlisting process. The model automatically excludes any cases of incomplete data. The final analysis contained 110 cases (47 medial compartment arthritis and 63 patellofemoral arthritis).

In block 0 (with no co-variable) the classification table had a 57.3% accuracy; this improved to 88.2% in the model including the co-variables. This suggest that the addition of co-variable data added considerable value to the predictive nature of the model.

Hosmer and Lemeshow goodness of fit had a chi-square of 3.8 with was non-significant,  $p=0.87$ . This indicates that the model is a good fit; although the Hosmer and Lemeshow test is considered flawed by many authors, being a significance test it is sensitive to sample size. A further two R tests can also be derived from SPSS for goodness of fit: Nagelkerke test found that 73% of the variance was explained by the model, whilst Cox & Snell R found this to be 51%, the -2 log likelihood was reduced from 87.9 to 62.1. This indicates that the new model is explaining more of the variance in the outcome and is an improvement on the 0 block model.



Co-variable	Wald statistic	Sig. of Wald stat.	Exp(B)	95% CI for EXP (B)	
				Lower	Upper
Sex	10.34	0.001	11.94	2.64	54.17
Patella height classification	7.56	0.006	8.93	1.88	42.56
Dislocation history	0.21	0.649	.224	0.22	11.08
Age unstable	21.00	0.000	.870	0.82	0.92

**Table 10. Output of multivariate analysis. EXP (B) is the odds ratio of having PFJ replacement as compared to medial replacement arthroplasty.**

The Wald statistic is significant in all of the co-variables except for dislocation history, where the p value is 0.060 and the 95% confidence interval straddles one. Female sex patients had a 11.9 higher odds ratio of presenting with severe patellofemoral arthritis than male sex patients. Patients with patella alta (defined as an ISR > 1.32) were found to have an increased odds ratio of having patellofemoral arthritis of 8.9. Both findings have p values of less than 0.05 and have confidence intervals that do not cross one.

Age of first instability is also a statistically significant finding, as there is a negative association between advancing age of first experienced knee instability and patellofemoral arthritis when compared to unicompartmental medial arthritis.

## Discussion

The study indicates that gender, young age at first episode of patella dislocation and elevated patella height are more associated with patellofemoral arthritis than with medial compartment arthritis. One of the most striking findings was the age of first onset of symptoms; Figure 17 illustrates how in the patellofemoral group the symptoms first affected at a much earlier age. This is consistent with the presentation of patellofemoral instability and patella maltracking.

## Strengths & weaknesses

This research offers new and unique findings to the literature and is based on large study sample. The advantage that we have here in Bristol is that the volume of patellofemoral replacements performed exceeds that of any other centre. As the hospital is the originating hospital for the design of the first patellofemoral implant the records have been kept accurately, permitting recruitment of a larger number of subjects than may otherwise be possible.

The choice of control group proved effective in tackling several potential concerns. The use of another group of patients with partial knee arthritis matched not only the biological effect that the arthritis may have on the tendon length but more importantly the experience of arthritis, pain and healthcare that the patients may have experienced.

For this retrospective study, the only consistent imaging available from the pre-operative period for these patients was a plain radiograph in the anterior-posterior plane and the lateral plane. It would have been useful to assess all the anatomic factors that can contribute to patellar instability including trochlea dysplasia, lateral tuberosity position and patella height. The trochlea is often deformed by the arthritic process so cannot be consistently assessed for dysplasia. The tuberosity position cannot be assessed except by axial imaging. For this reason, assessment was restricted to patella height on the lateral radiograph. The method of assessment of patella height on the plane radiograph, including by the Insall-Salvati ratio, is covered in a later chapter (Insall and Salvati, 1971).

An additional weakness is the paucity of data available in the database on patient weight and height. The effects of body mass index could have been explored with the questionnaire. Additional co-variables that could have been gathered via the questionnaire include presence of generalised arthritis and family history of joint hypermobility or arthritis. It would also have been possible to gather information on joint laxity (which can be measured by a self-administered Beighton questionnaire (1988)). These omissions represent a missed opportunity. I relied on existing records to screen for height and weight, which I later realised were of low yield.

The term “research in reverse” summarises the problems associated with all case controlled studies (Schulz and Grimes, 2002). The directionality of the research creates several challenges to the validity of this research.

Identifying and controlling for confounders can be a major challenge. In this study there was an opportunity to identify and manage the confounders by screening for them in the questionnaire. Multivariate analysis permits that potential confounders be included as a co-variable so that they are weighed and controlled. The omission of a hypermobility scale score that could have been derived by inclusion in the questionnaire is regrettable.

Another aspect of the retrospective nature of this research which creates a challenge is the measurement of patella height. The radiographs are not calibrated for length and therefore relied on a ratio of another length within the field. The measure relies on a ratio of the patella length and the patella tendon length. The assumption was made at the outset of the study that as the osteoarthritis is a loss of the cartilaginous bearing surface there would be no significant effect on the patella length. Incidental observations throughout the data collection was that in some cases the patella bone was deficient. I have retrospectively compared the absolute length of the patella in each group. The mean absolute length of the patella was 42mm (31-54, SD 5.46, IQR 5.3) in the patellofemoral arthritis group and 46mm (32-58, SD 4.4, IQR 5.3) in the medial osteoarthritis group. These measurements are made from uncalibrated radiographs and may be meaningless. If I were to repeat the study I would do so using a different denominator than patella bone length for the tendon length ratio.

Another question raised during the research concerns the effect that the arthritis may have on tendon length. An attempt was made to control for this by choosing the medial knee arthritis patients as the control group but the problem remains unquantified. Several pathologies are known to cause shortening of the tendon including trauma and tendon surgery. One study did demonstrate no discernible change in tendon length secondary to patellofemoral arthroplasty (Clark et al, 2012), this remains an unquantified issue.

### **Findings, the literature and implications for clinical practice**

Previous investigators have made the observation that an inherently unstable joint has thicker cartilage (Shepherd and Seedhom, 1999). It would appear logical that any disturbance of this most unstable joint would lead to unbalanced loading of its chondral surfaces and subsequent accumulated damage. The finding that patella alta is associated with patellofemoral arthritis is in natural continuity with previous biomechanical studies which have demonstrated

overloading of the cartilage in the presence of patella alta (Yamaguchi and Zajac, 1989; Hirokawa, 1991; Meyer et al, 1997; Ward et al, 2005; Luyckx et al, 2009).

The findings that symptoms appear to have an early onset as compared to medial compartment arthritis point to a biomechanical aetiology as opposed to a failure of defective cartilage.

### **Future work**

There is a subset of young patients with patella alta and degeneration of the distal pole of the patella. Although this study does not in itself provide a surgical indication for distalisation of the patella in these patients, it does add to the body of evidence that supports this approach. There are currently no major studies of the outcomes of surgery for distalisation of the patella in young patients with degeneration of the distal pole of the patella. A randomised controlled trial would provide an objective assessment of any benefit that the patients may or may not expect.

It can be proposed that osteoarthritis and patellar instability share the risk factor of patella alta. There are weaknesses to the study that could be addressed with a longitudinal study; this could involve patella height measurement in a large group of young patients which includes following them for 20 years to observe the effects on the development of symptomatic arthritis. A pragmatic way of performing this might be to use MRI data from some of the large studies discussed in the introduction. Some of these studies are more than 10 years old and so 20-year data are less than a decade away. It would be very important that the outcome of this study be severe symptomatic arthritis, not simply arthritis.

This study has highlighted that the congruence of this most unstable joint is poorly understood. The joint congruence may be a significant factor in the development of arthritis. This led me to the methodology in Chapter 2, where observations of the joint congruence in the normal and unstable patella are made.

## Chapter 2a: Measures of congruence in the unstable joint

### Introduction

I reviewed the literature relating to measurements of the patellofemoral joint I was looking for a technique that would provide an assessment of the congruity of the joint. Bearing in mind the definition of patella instability, that is well summarized in this statement “the patella may escape partially or completely from its asymptomatic position with respect to the femoral trochlea under the influence of displacing force.” (Post and Fithian, 2018) I aimed to assess the joint in a manner that approximated as far as possible the conditions during ambulation.

### Described patellofemoral measurements

The following section includes descriptions of patella anatomy, trochlea anatomy, limb torsional alignment, patella height, joint contact area (congruence) and the effect of muscle activation.

### Descriptions of patella anatomy

The patella is the largest sesamoid bone and has the thickest hyaline cartilage in the body, up to six millimetres. There is an association between the incongruent joint and cartilage thickness. In comparison the constrained and congruous hip joint has relatively thin cartilage on the acetabular side (1.2-2.25mm) (Shepherd and Seedhom, 1999). Shepherd and Seedhom remarked upon a gradient noticed in the distal femur, the thickest cartilage is associated with the trochlea and femoral condyle has a thinner covering

In 1976 Goodfellow and Hungerford outlined the anatomy of the articular surface, describing the area of contact with the femur through flexion. A typical patella can be divided into six articulating facets, a central vertical ridge divides the medial and lateral sides, the medial and lateral sides being divided into thirds. A seventh “odd facet” on the most medial portion of the medial facet is delineated by a further medial vertical ridge. Each facet articulates at different point during flexion, travelling from proximal to distal through flexion and then rotating in deep flexion to rest on the odd facet and the lateral facet.

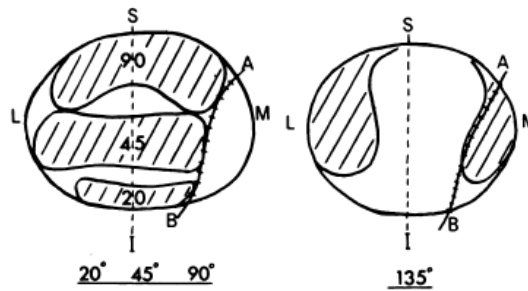


Figure 21. Sites of patella contact at different positions of knee flexion, Goodfellow et al 1976.

Wiberg’s description of the patellofemoral joint in 1941 is frequently quoted as being the first description of the range of patella anatomy seen. Wiberg’s thesis was more than a description of patella anatomy, he set out to use radiographic imaging to fully describe the patellofemoral joint and to explain instability. He describes a classification of the patella in the introduction that was to be used throughout the rest of his thesis and continues to be used today. “It was possible, in fact, to distinguish three different types as regards the shape of the patella...In a number of instances, the ridge was seen to be situated in middle of the patella, so that the medial and lateral facet were equal...in the second type, the ridge was situated slightly towards the medial border of the patella, and the medial facet was smaller than the lateral... the case in which the ridge was displaced medially to such a degree that there was hardly any room left over for the medial facet, with the result that the latter sloped forward and medially, constituted a third type.”

Wiberg acknowledges that these observations are based on a small number of patients, with only one case of “type three” patella. Despite this the description persists and is often quoted. Wiberg makes several significant observations regarding the patella anatomy; he described the concave lateral facet and, the convex medial facet. Wiberg made the first attempt at direct observation of the patella motion with an arthroscope concluding, “There was no possibility of studying the mechanism of the joint. No clear enough idea could be gained of the gliding movements of the patella towards the femoral condyles to allow conclusions to be drawn.”

Baumgartner described a variant of the “type three” patella where a projection of the medial facet contacts the medial femoral condyle, he attributes this as a cause of medial femoral condyle osteochondritis dissecans. Grelsamer et al studied patella radiographs, analysing the shape of the patella as it appears in the sagittal plane. They noted the length of the articular patella is not constant to the non-articular portion. The mean ratio was 1.4 in asymptomatic knees and they defined three patella types. Type I had a ratio of 1.2-1.5 and constituted 94% of patellae. Type II constituted 4% of the sample and had a ratio of more than 1.5, with a long

inferior pole where also called “Cyrano” patellae after the long nosed Hercule-Savinien de Cyrano de Bergerac. Those with a ratio of less than 1.2 constituted 2% and were called type III. In a group of patients with patellofemoral pathology they found a higher proportion of patients with type II and III patellae (76% type I, 17% type II, 7% type III) than in the normal population. This work is often quoted but does not impact on clinical work.

One author evaluated patella width to address a clinical problem. The mechanical advantage enjoyed by the patella is a function of the thickness of the patella, variable amounts of bone and cartilage may be worn in arthritis. In 2015 Sullivan et al described a constant relationship between patella width and thickness, useful when replacing a worn patella so as to calculate what thickness should be restored.

## **Descriptions of trochlear anatomy**

### **Trochlear dysplasia**

The first description of trochlear dysplasia pre-dates the first radiograph. The description from Richerand in 1802 discussed three patients with patellar instability who had lower lateral condyles than medial. Since then several authors have used radiographs and axial imaging to describe the anatomy of the trochlea. Observers have commented on the relative height of the two condyles on the axial view of the patella. Early authors did not acknowledge that a rotation of the distal femur or a rotation of the radiograph film will present an “illusory dysplasia”.

### **Condyle height**

Brattstrom worked in Sweden in the department run by Gunnar Wiberg. Several previous authors had commented on the relative height of the femoral trochlear on the axial radiograph. There had been many criticisms, as there did not seem to be any way of standardising the rotation of the femur. The rotation of the femur can substantially alter the appearance of the trochlea height as measurements are taken from the base of the trochlear groove. Brattstrom overcame this problem by first securing his patients in a chair with leather straps and then performing an antero-posterior radiograph so that the posterior condyles could be seen and then performing an axial radiograph. Fine wires were placed horizontal to the floor in the field of view on both films so that the rotation could be standardised. The technique did not permit visualisation of the epicondylar axis as would now be possible with computed tomography. The posterior condylar axis is unreliable and may not be as functionally relevant

as the epicondylar axis in knee extension (Tanavalee et al, 2001). The major limitation of this study is the leg position, the radiographs were performed in 90 degrees of flexion, with the beam angled at 30 degrees. We now know that most instability occurs towards the final 40 degrees of extension.

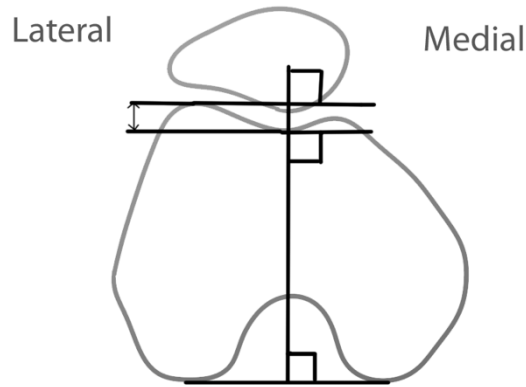
Despite these technological limitations Brattstrom applied considerable rigour to his investigations and produced a sound basis for subsequent investigations. Brattstrom investigated condylar height relative to a horizontal line, rather than the posterior condylar axis. He examined 100 men and 100 women with no known knee problems. He found no difference between the condylar height due to association with age or body length. Gender had minimal influence, describing the female condyle as “more delicate” but with a similar torsional profile and skeletal position. Brattstrom found a statistically significant difference between the left and right knee in both males and females. He states that in the left knee there is greater external torsion or rotation (his experiment can not tell us which). He felt this difference was marked enough that side specific controls would be required in future studies.

In the second half of his thesis he examines the condylar height in normal knees and knees with patellar instability. In this study, however, he relies on radiographs taken throughout Sweden that do not apply his fine wire technique. Brattstrom finds non-statistically significant lower condylar height in the instability patients when compared to patients with normal knees. These are not standardised for rotation or trochlear depth and this is acknowledged in the text.

### **Trochlear depth**

Martinez et al (1983) performed CT scans of normal patellofemoral joints. They evaluated two axial slices at the junction of the middle and distal third of the trochlear and at the junction of the middle and proximal third in 20 patients. They evaluated femoral trochlear depth amongst other parameters. Femoral trochlear depth was defined by drawing two lines parallel to the posterior condylar axis. One line passes through the most anterior prominence of the lateral femoral condyle and the other through the base of the trochlear groove. The authors performed these CT scans with the knees in various degrees of flexion and with and without quadriceps activity. They recreated quadriceps activation by asking the patients to suspend their legs 2-4cm above the scanner bed. The measurement varied dependent on degree of knee flexion and on quadriceps activation. They noted the femoral trochlea depth measurement was unaffected by the knee flexion angle.





**Figure 22. Sulcus depth, reproduced from Martinez et al 1980. Defined by drawing two lines parallel to the posterior condylar axis. One line passes through the most anterior prominence of the lateral femoral condyle and the other through the base of the trochlear groove.**

Descriptions of the trochlea anatomy are often overlapping and only subtly different. Trochlear depth has subsequently been described by several authors (Pfirrmann et al, 2000; Malghem and Maldague, 1989; Kujala et al, 1989). It is calculated using an axial MRI view of the knee at three centimetres above the femoro-tibial joint. The distance between the posterior condylar axis and the most anterior part of the medial femoral condyle is measured and termed the medial condylar height; this is repeated with the lateral femoral condyle. The distance between the posterior condylar axis and the deepest point of the trochlear is measured (A-D in the diagram). The measurements to the condyles are averaged and the measurement to the trochlear is subtracted from this. This measurement was validated by Pfirrmann et al in 2000 as an assessment of trochlear dysplasia. They found a 100% sensitivity and a 96% specificity when comparing a group of patients with trochlear dysplasia with a group of patients without trochlear dysplasia. The patients were selected by consensus opinion from two radiologists who decided that they had dysplasia based on the presence of crossing sign (described later in text) on a lateral radiograph. The paper does demonstrate that dysplasia can be measured in a manner consistent with the opinion of radiologists and suggest that it may be a useful research tool. Their idealised axial image of the distal femur is reproduced below.

### **Trochlear inclination**

Trochlear inclination angle is intended to indicate the rotation of the trochlear within the femur. The angle is composed of a line drawn between the most prominent anterior points on the condyles and another line drawn perpendicular to the antero-posterior axis of the knee. In 2012 Kamath et al found an association between dysplastic knees and a reduced internal rotation of the trochlear. Internal rotation was  $9^{\circ}$  ( $4-15^{\circ}$ ) in knees with trochlear dysplasia and  $11^{\circ}$  ( $6-20^{\circ}$ ) in those without. The measurement relies on not only the lateral condyle height but

also the medial. The lateral patella facet anatomy is known to be consistent between knees in the same patient and along its length (Brattstrom, 1964). The lateral trochlear is the more functionally relevant and so referencing the medial trochlear may or may not be relevant, this may be why most investigators have used the lateral trochlear inclination as an indicator of trochlear rotation.

### External (lateral) trochlear inclination

In 2000 Carrillon et al described an angle between the lateral facet of the trochlear and the posterior condylar axis as the lateral trochlear inclination. They undertook a study to determine the sensitivity and specificity of this measure in the assessment of symptomatic trochlear dysplasia. They took a group of 30 consecutive patients with two documented episodes of patella dislocation as diagnosed on examination by the attending doctor, age range 15-42 (mean 24). The control group comprised of 30 age and sex matched patients who had undergone MRI for internal derangement of the knee. They performed static MRI scan and evaluated the most proximal axial image of the trochlear for each patient. Lines were then drawn tangential to the lateral condyle and along the posterior condylar axis. They found a threshold of  $11^\circ$  to be significant; 28 of the patients with instability having less than  $11^\circ$  of trochlear inclination and 26 of the patients without instability having more than  $11^\circ$  of trochlear inclination. The receiver operating characteristics indicate 95% area under curve with excellent sensitivity and specificity of the test.

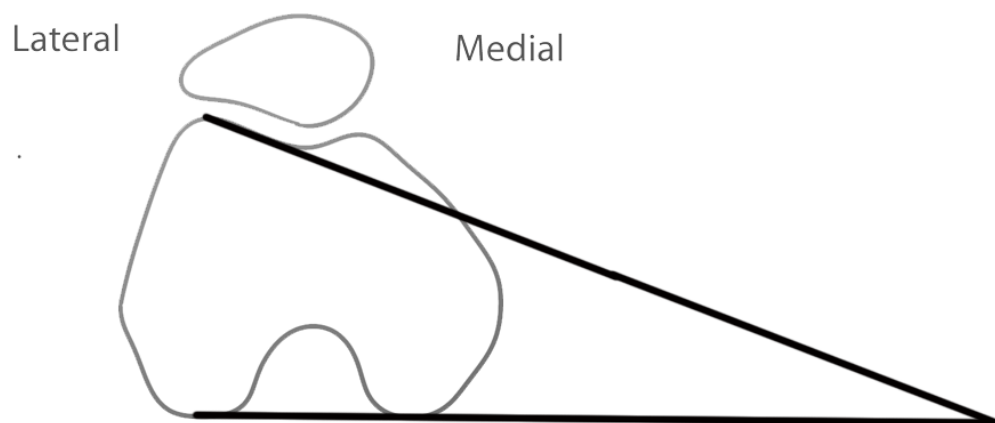


Figure 23. External (lateral) trochlea inclination, reproduced from Carrillon et al 2000. Angle subtended by line drawn tangential to the lateral condyle and along the posterior condylar axis

### Facet asymmetry

Facet asymmetry was evaluated on radiograph by Brattstrom. Facet asymmetry was later evaluated on MRI scan by Pfirrmann (2000) with an axial slice 3cm above the tibiofemoral joint. They measured the length of each facet and created a medial to lateral ratio. They established in a group of 16 patients with dysplasia and twenty three patients without dysplasia that a facet ratio of less than 2:5 (medial:lateral) had a sensitivity 100% and specificity of 96%.

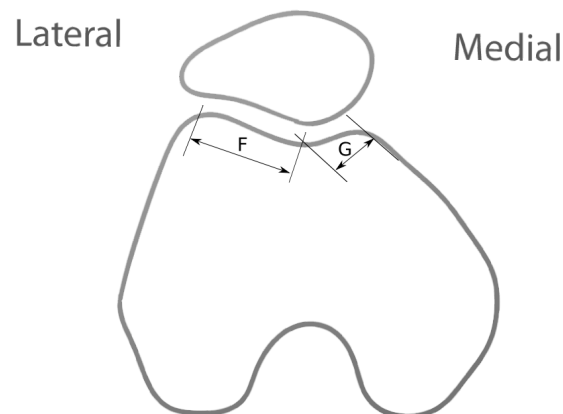


Figure 24. Facet asymmetry, from Brattstrom et al 1959. Medial (G) to lateral (F) ratio of each facet.

### Nipple positive

Pfirrmann et al (2000) described the presence of a prominence on the lateral radiograph of a lump in the proximal trochlea as a “nipple”. Such prominences have been observed by previous authors. The height of the nipple was recorded by Pfirrmann and found to correlate with the presence of trochlear dysplasia. Sensitivity was 69% and specificity 91%.

### Sulcus angle

The sulcus angle (or femoral trochlea angle) was first described by Brattstrom (1959) and Hakan (1964) and subsequently used by Martinez (1983) . They sought to describe differences in the trochlear between normal volunteers and those with a minimum of one episode of dislocating patellae. The sulcus angle is a description of the trochlear. Unlike the other measurements it does not describe the relative positions of the trochlear and the patella. The sulcus angle is measured by drawing a line from the most anterior condylar point on the medial side down to the deepest part of the trochlear and then from the most anterior condylar point on the lateral side down to the deepest part of the trochlear. The angle is measured between these lines.

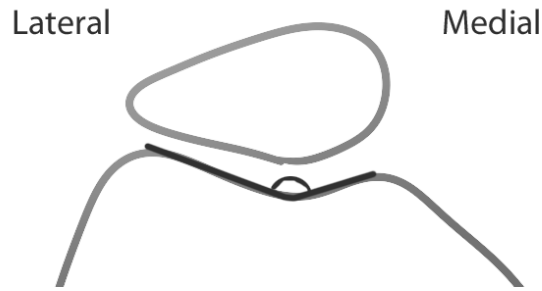


Figure 25. Sulcus angle, reproduced from Hakan et al 1964. Subtended by a line from the most anterior condylar point on the medial side down to the deepest part of the trochlear and then from the most anterior condylar point on the lateral side down to the deepest part of the trochlear.

### Condyle depth asymmetry

Pfarrmann (2000) sought to standardise description of trochlea morphology by describing a plethora of measurement relating to the distal femur when the axial image was assessed 3 cm above the femorotibial joint space also used the “condylar height” described in the trochlear depth paragraph to create a ratio of medial to lateral condylar height (A-B in the diagram). They did not find any correlation between this measurement and the presence of trochlear dysplasia. The study described a number of previously used measurement, such as trochlea depth (A-C) in these terms. It is a particularly useful paper to others who seek to describe anatomic abnormalities of the distal femur. The complexity of this study, that describes the anatomy at only one axial point (3cm above joint line) and has numerous metrics (A-F) highlights the difficulty in describing the shape of the femur. When we add to this abnormalities of the patella and it’s movement we can see that the anatomy can not be easily summarised in a few simple measurements.

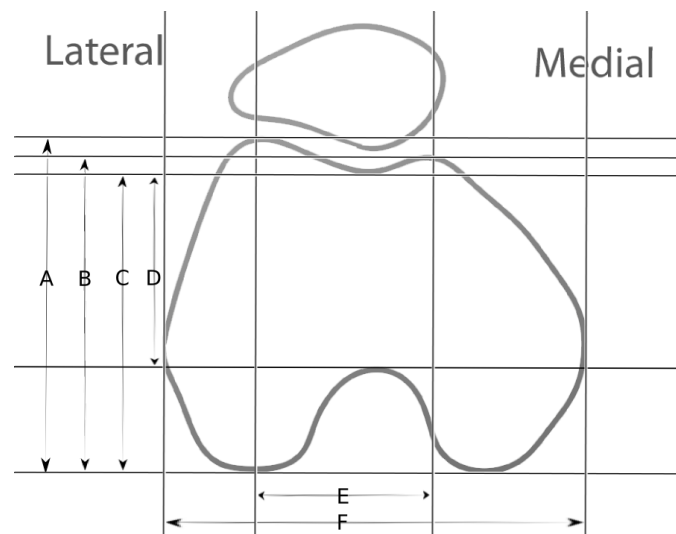


Figure 26. Standardized distal femur, reproduced from Pfarrmann et al 2000.

## Dejour

Henri and David Dejour are the most celebrated authors in the patellofemoral literature having popularised the crossing sign. The sign is usually associated with his name although Henry Dejour credits it to earlier authors (Maldague B, 1985).

This is seen on a standard lateral radiograph; perfect lateral views are required with the condyles superimposed upon one another. The crossing sign is found in this projection and represents the point where the trochlea becomes flat, where the bottom of the trochlea groove reaches the height of the facets. Other features include findings of the double-contour sign and supratrochlear spur. The double contour represents the hypoplastic medial facet found posterior to the lateral facet. The supratrochlear spur is found in the superior aspect of the trochlea.

The later 1998 Dejour classification is the most universally adopted classification of dysplasia. A classification system was proposed by David Dejour. Dejour takes a more categorical approach than Pfirrmann's scalar approach. The Dejour classification evaluates the overall shape of the joint and fitting individual each into one of four broad categories. It may be this ability of the classification to summarise the anatomy that has led to its popularity.

- A) A normal shaped with a shallow trochlear groove.
- B) Very flat or convex trochlear
- C) Asymmetric trochlear facets lateral facet too high and medial facet hypoplastic, this results in the flattened joint surface forming a single oblique plane
- D) The features of C and a vertical link between medial and lateral facets.

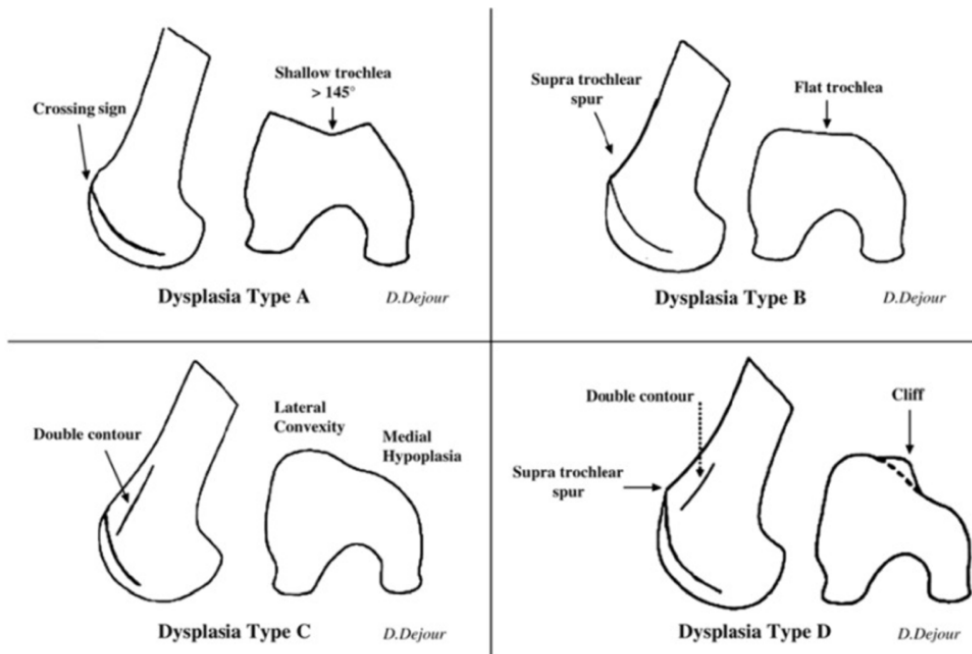


Figure 27. The Dejour classification, 1998. This is a non-ordinal classification. Best fit according to patient's morphology.

## Descriptions of lower limb torsional profile

### Femoral anteversion

Femoral anteversion is a description of the angle of the femoral neck to the epicondylar axis of the distal femur (Beaconsfield et al, 1994). Excessive femoral anteversion is termed as internal femoral torsion, reduced femoral anteversion is termed as external femoral torsion. It is a measurement commonly made in hip surgery. In the context of limb alignment, the measurement is made between the femoral neck and the distal femur. An axial slice of the hip joint and the knee are overlaid. The angle is measured between a line defining the axis of the femoral neck and the posterior condylar axis or the epicondylar axis.

### External tibial rotation

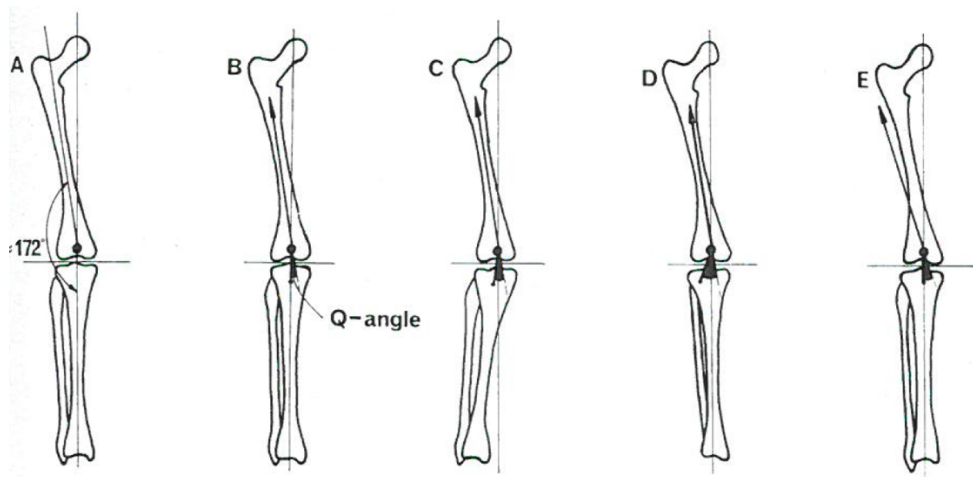
External tibial rotation can be measured by overlapping an axial image of the proximal tibia and the ankle (Beaconsfield et al, 1994). On the slice of the proximal tibia a line is drawn along the most posterior aspect of the tibia and in the ankle between the condyles. The angle between these lines will give some indication of any rotational deformity in the tibia that is contributing to the pathology. This measurement is not validated and appears scarcely in the literature. The measurement relies on the posterior ridge of the tibia being functionally consistent, which it may not be.

## Condylo-malleolar angle

The condyle-malleolar angle is measured by overlaying axial slices taken from the ankle and the distal femur, the measurement crosses the knee joint and it is dependent on knee position and any correctable malposition due to leg position (Beaconsfield et al, 1994). The angle is composed of the intercondylar angle and a line drawn along the posterior condylar axis. Like the external tibial rotation angle this measurement is not validated. The described measurement relies on the use of the posterior condylar axis, the posterior condyles are a curved surface so their most prominent point depends on where in the curve the slice is taken. A more reliable alternative would be to use the epicondylar axis (Tanavalee et al, 2001).

## Q-angle

The concept of the quadriceps angle (Q-angle) is frequently credited to Brattstrom (1964). It is an angle formed between the vector of pull of the quadriceps musculature and a line drawn from the centre of the patella to the tibial tuberosity. The physiological valgus of the human knee is 8-10° in the male and in the broader pelvis female this may be 10-12°. The lateral forces on the patella are increased where the Q-angle is increased and many authors have demonstrated a relationship between patellar instability and an increase Q-angle. Brattstrom references several other authors as having described causes of an increased Q-angle.



**Figure 28. Normal and abnormal Q-angles. Image from Brattstrom's thesis, 1964. A&B, normal Q-angle. C, increased Q-angle due to valgus position of the skeleton. D, Increased Q-angle due to lateral attachment of ligamentum patellae. E, Q-angle increased due to quadriceps muscle resultant force is more lateral than normal.**

As the knee extends the tibia externally rotates, particularly in the last few degrees of extension. This final external rotation increases the Q-angle further. The Q-angle may be further altered by valgus alignment of the lower limbs, muscular imbalance with weakness or deficiency of the medial quadriceps or by a lateral position of the tibial tuberosity.

### Tibial tuberosity to trochlear groove distance on radiograph

The tibial tuberosity to trochlea groove (TTTG) distance is a development of the Q-angle. The measurement makes the assumption that by assessing the laterality of the tubercle position an assertion can be made regarding the vector that is placed upon the patella. Goutalier (1978) described a technique with a subtle modification of the Merchants view. With the patient supine the knee is placed at 30 degrees of flexion. A radiographic image is taken in almost the horizontal plane so as to include the tibial tubercle and the trochlea in the same image. The distance between them can then be measured. Confounding variation may arise if the femur is permitted to internally or externally rotate. The authors evaluated normal patients (n=16), arthritis patients (n=30) and instability patients (n=24). Amongst the normal knees they described a mean of 13mm range (7-17mm). Although the mean is not given amongst the arthritis patients the range was higher (16-31mm) and amongst the instability patients higher again (9-38mm). They recommend this as a technique for assessing the degree of correction required at surgery.

### Tibial tuberosity to trochlear groove distance on MRI

The Sixiemes Journees Lyonnaises de Chirurgie de Genou in Lyon presented over thirty papers on patella surgery. Amongst them was a study of rotational and patelofemoral indices amongst patellar instability patients (Walch, 1987). The authors divide patients into three groups defined as major instability (habitual dislocation), objective dislocation (at least one recorded dislocation on radiograph or on examination, potential dislocation (no history of dislocation but a feeling of instability or pain) and control patients. They found statistically significant differences between the control groups (mean 10 mm) and the instability groups.

Group	n	Mean TTTG
Major instability	16	20
Objective instability	217	18
Potential instability	53	15
Control	60	10

**Table 11. From “Sixiemes Journees Lyonnaises de Chirurgie de Genou”. Results of a study of rotational and patelofemoral indices amongst patellar instability patients indicating that greater instability was associated with increased TTTG.**

They concluded that “normal TTTG is 10-12 +/- 4 (Tuneu, 1987), a TTTG of more than 20 mm should prompt surgery. The image below is from a later paper but illustrates the technique well (Dejour et al, 1994). The tibial tuberosity (shaded) is superimposed over the trochlea (clear). Translation parallel to the posterior condylar axis is measured in millimetres.

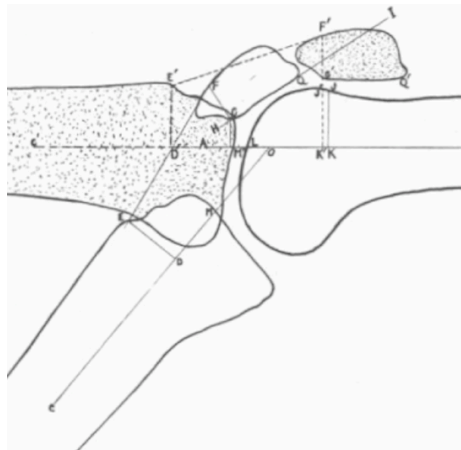


The measurement has been validated by Amis's group (Stephen et al, 2015). In a cadaveric study they evaluated patellofemoral contact pressures and tracking at 0°, 10°, 20°, 30°, 60°, and 90° of flexion using pressure-sensitive film and an optical tracking system. It demonstrated that an MPFL reconstruction could control the patella tracking up to a tolerance of a TTTG of 15mm. If the TTTG exceeded 15mm then the kinematic remained abnormal despite the reconstruction.

## Descriptions of patellofemoral relations in the sagittal/lateral plain

### Boon-ITT

The fascination of the orthopaedic community with patella height and its assessment by plain radiograph began with a paper in the American Journal of Roentgenology (Boon-Itt, 1930). Writing from Siam, Boon-Itt comments on the state of knowledge, that a low patella can result in pain and that a high patella can result in instability. Boon-Itt evaluates 200 normal radiographs taken without standardization of flexion position or magnification. He developed a complex mathematical standardizing of patella height irrespective of knee flexion position. The method acknowledges the importance of patella height to the mechanics of the joint, the importance of cartilage contact and of knee flexion. The technique has proved too complex for clinical practice, no method since has addressed all of the issues that this method tackles.



**Figure 29. Image from Boon-Itt et al, 1930. A complex calculation permits patella height to be calculated without the need for standardization of patella height.**

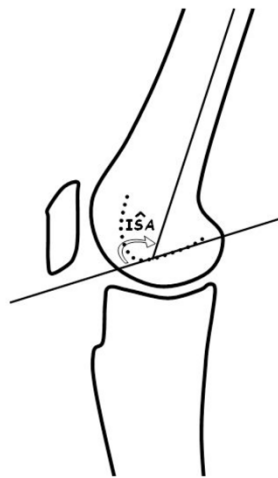
Boon-Itt's other major contribution comes with his reference to using another measurement in the radiograph to create a ratio and thereby standardize the magnification. He also highlights the importance of standardizing the position of the knee.

### Blumenstat's line

Blumenstat (1938) made one of the first attempts to find a clinically useful measure of patella height. He recommended that a lateral knee radiograph be obtained at 30 degrees of knee flexion and that a line be projected along the intercondylar shelf. This line should transect the distal pole of the patella. A perfect lateral radiograph is rarely obtained and to have one at 30 degrees of flexion precisely is very rare and even when that is achieved there is variation in the shelf angle (Blumensaat's line).

### Seyahi

Seyahi (2006) brought about a rebuttal of the technique. They demonstrated that even when the radiograph was performed at 30 degrees the technique was inaccurate. Seyahi only had normal radiographs available and quotes poor correlation between the technique and the other height measurement technique as a weakness. He also suggests this discrepancy may be due to variations in the intercondylar shelf angle which he measures as  $146.73 \pm 3.21^\circ$  (range 139 to 144°) in the Turkish population. They went as far as developing an adjusted Blumensaat line but found that also to be inaccurate.



**Figure 30. In the normal situation Blumenstat's line intersects the inferior pole of the patella with the knee at 30 degrees of flexion. Image from Seyahi et al 2006. Blumensaat's Line is the solid line perpendicular to the femoral axis in this image, it follows the intercondylar shelf, illustrated by the dotted line in this image. Variations in the angle ISA illustrate that variations in the intercondylar shelf render the technique inaccurate.**

### The Insall-Salvati ratio

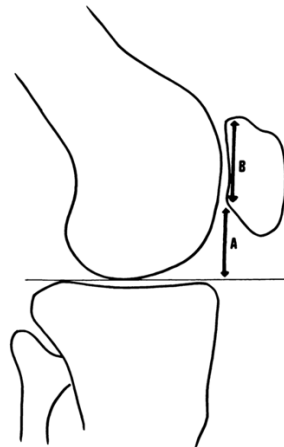
The 1971 Insall Salvati Ratio is the most widely recognised patellofemoral index. The ISR describes the height of the patella by creating a ratio of patella tendon length to the maximum diagonal length of the patella. They state that the length of the tendon (LT) is

approximately equal to the length of the patella (LP) with a mean LT/LP of 1.02 in 114 knees without known patellofemoral pathology. This finding has been confirmed by others (Jacobsen and Bertheussen, 1974). Insall's further work demonstrated an average ISR of 1.23 in 37 patellar instability patients. Convention is that an ISR of more than 1.2 is known as patella alta whilst an ISR of less than 0.8 is known as patella baja (or patella infera).

### The Blackburne-Peel ratio

The Blackburne-Peel ratio (1977) is one of two ratios, the other being Caton-Deschamps, to reference the tibiofemoral joint line. Blackburne and Peel described a method of assessing patella height where a line is projected along the tibial joint line and two measurements are made, the perpendicular distance from the line to the lower end of the articular surface of the patella and the length of the patella articulation. They made two criticisms of the ISR. Firstly, that the inferior pole of the patella is included in the measurement, this is not articular and is subject to some variation (as discussed by Wiberg) so may distort the reading of patella length. Secondly that the insertion of the tendon may be difficult to identify.

In their study of 171 knees without patellofemoral pathology they defined a normal Blackburne-Peel ratio of 0.8.



**Figure 31. Blackburne-Peel ratio, image from Blackburne-Peel 1977. A line is projected along the tibial joint line and two measurements are made, the perpendicular distance from the line to the lower end of the articular surface of the patella and the length of the patella articulation**

Aglietti (1983) also evaluated the use of the Blackburne-Peel ratio in knees with patellofemoral pathology and in those with instability. They found that the mean ratio in the control group was 0.91 and in patellar instability, 1.08 (range 0.76-1.89).

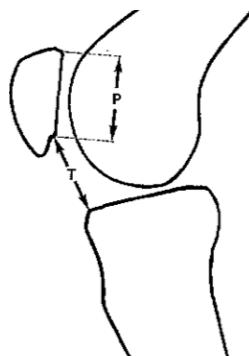
### The Laurin-Labelle technique

Laurin (1977) makes reference to evaluation of the patella height on a lateral radiograph with the knee flexed to 90 degrees. With the knee flexed to a right angle a line is drawn along the anterior cortex of the femur, Laurin proposes that in patella alta the proximal tip of the patella will lie well above this line. No data in favour of the technique was offered by the author. The technique was assessed by Seil et al in 2000 who found it to have good inter-observer correlation but made several criticisms of the technique. They state that a radiograph at 90 degrees of flexion is not routinely attained and that the anterior bow of the femur gives rise to great variability in the anterior femoral cortex.

### The Caton and Deschamps ratio

In 1982 Caton and Deschamps further modified the Blackburne-Peel method. They also referenced from the tibial joint line but criticised the use of the projected line from the tibia. Instead they recommended using the most anterior corner of the tibia and measuring directly from here to the patella joint surface and then creating a ratio between this and the patella joint surface. They defined patella infera as less than 0.6 and patella alta as more than 1.3. The 1984 Linclau method makes the same measurements but the ratio is inverted.

In Denmark de Carvalho et al (1985) used the methods of Caton and Deschamps. They assessed the technique on 150 normal patients and evaluated the variance using this technique and that of Insall and Salvati. They found the ISR to be unusable in 33 cases as the tendon insertion or inferior pole of the patella could not be clearly defined. They found that their own ratio could not be used in one case due to difficulty seeing the inferior part of the joint surface. The variance was less using the Caton-Deschamps technique (0.13) than when the ISR was used (0.17), even when these 33 cases were excluded. They concluded that this technique was a preferable alternative as so many cases had to be excluded for the ISR group.



**Figure 32. The Caton-Deschamps(b) ratio. Image from de Carvalho et al 1985. The most anterior corner of the tibia is measured directly from here to the patella joint surface and then creating a ratio between this and the patella joint surface.**

With the exception of the impractical Blumensaat's (Blumensaat, 1938) line technique and the Laurin technique none of the aforementioned measures of patella height consider the relationship between the patella and the trochlear. This is a significant omission. Caton and Deschamps criticised the Insall-Salvati ratio as the tuberosity could be moved to any point and it would not be affected. Caton and Deschamps ratio could also be criticised as variability in femoral anatomy means that although the height of the patella is considered the height of the trochlea is not.

### The Norman ratio

Norman et al (1983) raised a criticism of the ISR that it is not affected by transposition of the patella tendon insertion that undoubtedly affects patellofemoral kinematics. They developed a technique for describing patella height that used total body height as the denominator in its ratio. As body height is not measured on the radiograph it is necessary to standardise the radiograph. To use this technique the knee must be placed next to the radiographic plate and the radiation source must be precisely one metre away. The knee is placed in full extension and the patient contracts the quadriceps.

The numerator in this ratio is the height from a line projected from the tibial joint line to the inferior pole of the patella. The technique did not gain much popularity, it differs little from the other techniques which reference the tibiofemoral joint line and adds further complexity.

### Janssen

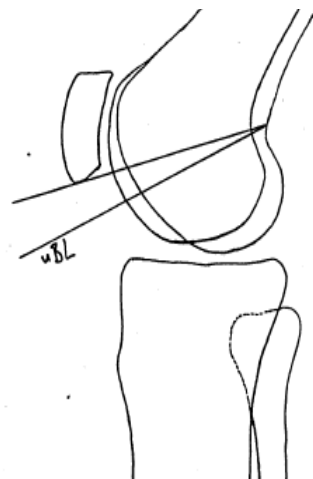
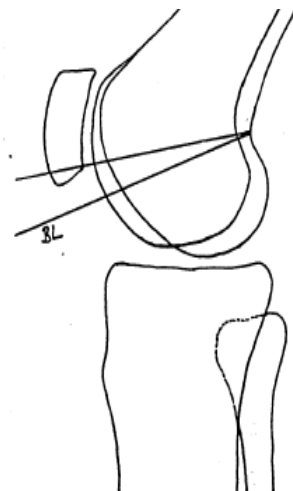


Figure 33. Janssen's method. Image from Hepp 1984. The angle measured is subtended by Blumensaat's line and the inferior edge of the patella to the posterior femoral cortex.

In Janssen's 1978 landmark paper on the aetiology of patella dislocation he also describes a further technique of measuring patella height (Patellahohenwinkel) . The angle

measured is subtended by Blumensaat's line and the inferior edge of the patella to the posterior femoral cortex. This method is an attempt to add an of quantification to Blumensaat's technique. The strength of this technique is that it references the two articulating bones rather than using the tibia, however the knee must be at precisely 30 degrees of flexion for the technique to be reliable.

In the 1984 German literature, Hepp described a modification of Jansen's work with a new measure of patella height , relying on the distal femur. The angle measured is subtended by Blumensaat's line and the superior edge of the patella to the posterior femoral cortex (normal range 32 to 53 degrees). As well as tweaking Jansen's angle Hepp contributes a table. As it is unlikely that the radiograph is at exactly 30 degrees of flexion the table enables modification of the value depending on the knee position. He compares his technique with those of Blumensaat, Insall and Blackburne in 360 control patients (patients with meniscal injuries) and 200 with a history of patella dislocation. The incidence of patella alta with the "patellahohenwinkel" technique is 26.5% in the instability patients and 2.8% in the control group. The incidence of patella alta with the Insall technique is 45% in the instability patients and 6.7% in the control group.



**Figure 34. Hepp modification of Jansen. Image from Hepp 1984. The angle measured is subtended by Blumensaat's line and the superior edge of the patella to the posterior femoral cortex.**

In the same paper he proposed another measurement: A distance perpendicular to Blumensaat's, line to the superior tip of the patella (58 to 37mm patella height range normal). The distance reduces with knee flexion; a modifier table was, made available to the reader. Hepp comments that "Measuring the height of the patella requires more knowledge and experience than is generally realized. There is still no convincing and absolutely reliable measuring method."

### The Micheli ratio

In 1986 Micheli et al\_ sought to access the hypothesis that rapid femoral growth contributed to patella alta. They proposed that traction on the musculotendinous unit ultimately contributed to the high position of the patella. They used serial leg length assessment radiographs taken in adolescent children to measure growth velocity. The study included 19 patients who were all being monitored for growth disturbance following a physeal fracture of the contralateral limb. Only antero-posterior radiographs are utilised in measuring growth disturbance so they developed a new measurement of patella height. They referenced Brassstromm's 1970 assertion that the definition of patella alta is the presence of the inferior tip of the patella above the tibial plateau. They used a Pearson's K coefficient correlation to look for correlation between femoral growth and patella height, they found one boy and one girl with a strong and statistically significant correlation between growth rate and patella height. Overall girls had a weak statistically significant correlation between patella height and growth velocity, there was no such relationship amongst boys. The authors recognise the limitations of the measurement technique, the knees are in full extension and the patella does not appear so clearly on an antero-posterior radiographic image. It is a small study and generates an interesting hypothesis, this was never followed up by a further larger study. The measurement technique is flawed as minor issues with rotational malalignment of the radiograph can alter the appearance of the tibial joint line.

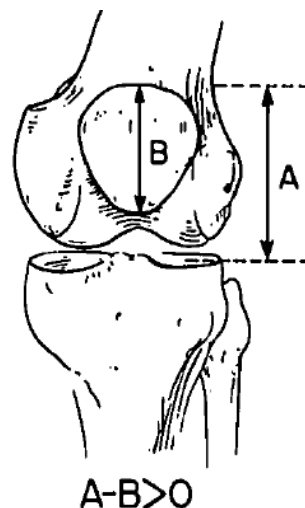


Figure 35. Micheli method. Image from Micheli et al 1986. A similar patella height ratio to the Blacburne-peel but performed with an AP radiograph.

### Egund ratio

In 1988 Egund et al attempted to overcome a number of the shortcomings of the previously described techniques. They were concerned that the denominator in the various

ratios in use was an unnecessary source of error and considered the use of the inferior tip of the patella as an irrelevant landmark of height. They also aimed to address the problem of the “baggy tendon”. They recommended a technique where the patient would stand leaning against an angled post to enable a consistent angle to be achieved and to load the tendon so that it achieve a reproducible height.



**Figure 36. Taking up the "baggy tendon" slack by knee flexion. Image from Egund et al, 1988.**

The measurement technique they describe aimed to reference the height of the patella from the distal femur on which it articulates. A line is perpendicular to the condylar plane of the femur and then a further line drawn perpendicular to this up to the midpoint and distal articulating cartilage of the patella.

They assessed three groups of patients, 47 volunteers from the hospital staff, 36 elderly patients with symptomatic knees and 16 young patients with knee pain. Performing lateral radiographs in the standing position illustrated. They found no difference between patella height amongst different sexes or ages or between the three groups. They did find a significant difference in patella height between standing and recumbent patients (mean 3mm, range 0-11mm).



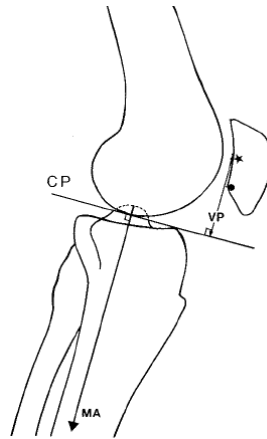


Figure 37. Egund ratio. Image from Egund et al 1988. The AP projected line is a similarity to the Blackburne-Peel ratio

### The Koshino and Sugimoto ratio

Koshino and Sugimoto (1989) working from Yokohama city in Japan tackled the problem of patella height in children. The particular problem they encountered was that as the patella had not fully ossified, its borders could not be readily recognised on a plain radiograph. The presence of the physal line on the femur enabled them to identify the upper limit of the trochlea cartilage and so this was included as a landmark. As the proximal tibia is largely cartilaginous in children they selected the middle of the tibial physis as the inferior landmark. The resultant ratio can be seen in the associated image.

In 59 knees of 36 children aged 3 to 18 they reported the ratio in full extension to be an average 1.31 (+/-0.9). Unlike previous authors they assessed the use of the ratio in several positions of flexion, commenting that it remained more consistent over the range than might be expected for the ISR.

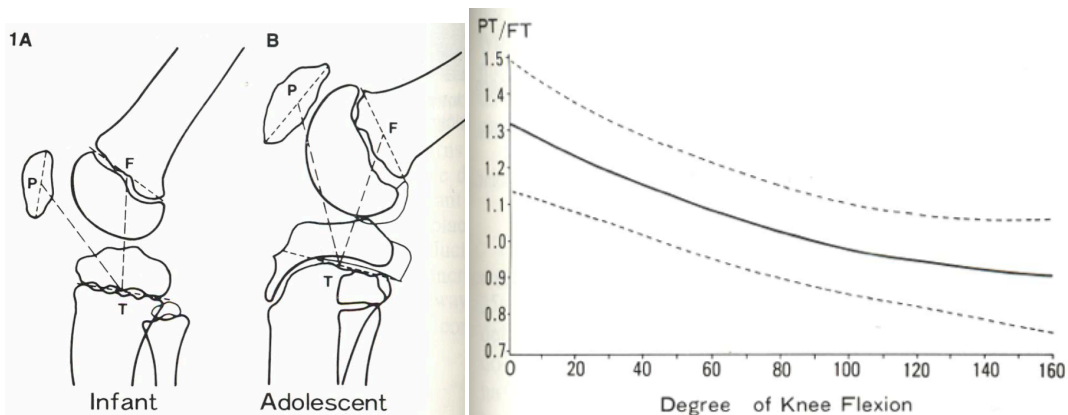
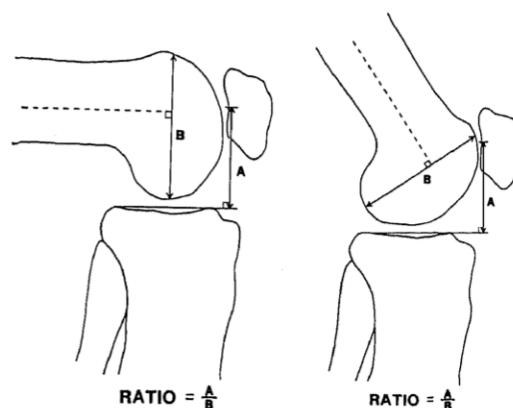


Figure 38. Koshino and Sugimoto ratio tackles the problem of the incomplete ossification of the bones by referencing central pints in the tibial and femoral physis and the centre of the patella. The graph on the right points to a relationship between measured height and knee flexion, from Koshino et al, 1989.

## The Burgess ratio

Burgess (1989) in Kentucky recognised the significance of describing the relationship between the patella and its articulation with the femur rather than just the tibia. He comments that the ideal ratio would be calculated with the knee at 90 degrees of flexion so that the height of the patella on the centre of the femoral trochlea may be assessed. Although this position has no special significance the width of the femur at that point is related to the trochlea anatomy and so may be a more relevant denominator in a ratio than patella length. He proposed that the height can be calculated in any position as long the width of the femur is measured and that it may be inferred from that. He then applies his own measurement and that of Insall and that of Blackburne to a cohort of 150 normal knees in order to determine which is the most reproducible. He finds his own ratio the most reproducible with a range of 0.56 to 0.76 considered normal. There may be some merit in the logic of standardising the height against femoral width rather than patella anatomy. The author doesn't however describe the technique in the presence of pathology and it has not been reproduced elsewhere in the literature.



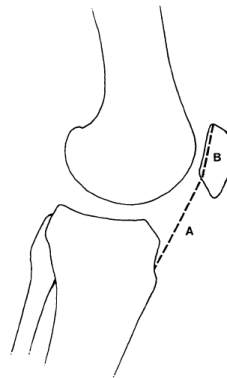
**Figure 39. Burgess ratio. Image from Burges et al 1989. Burgess imaged the knee at 90 degrees of flexion and utilized the femoral condylar width as the denominator in his ratio.**

## The Modified Insall-Salvati method

Gresalmer et al (1992) sought to evaluate the sensitivity of the Insall-Salvati ratio. They commented that the ratio was widely used and that it measured the length of the patella itself rather than the articular portion. They proposed another measurement, where the length of the patella would be replaced by the length of the articular portion, the advantage of this technique is that the variable patella morphology does not cause unwanted variance in the ratio denominator. They commented that the Caton-Deschamps technique (having demonstrated its equivalence to the Blackburne-Peel and De Carvalho techniques in a pilot study) was convenient and that was used as the gold standard. The authors reviewed the radiographs of

300 patients with a mix of knee pathologies by the Caton-Deschamps, Insall-Salvati and modified Insall-Salvati techniques. They found 36 cases of patella alta by the Caton-Deschamps technique. Ten of these were identified also by both the Insall-Salvati and modified Insall-Salvati technique, 18 (50%) by the Insall-Salvati technique and 28 (78%) by the modified Insall-Salvati technique.

The authors recommended using this modified technique. The weakness of this study is in its gold standard. There is no reference to patient outcomes and it is not known if the missed cases or indeed the identified cases, are significant.



**Figure 40. Modified Insall-Salvati technique. Image from Gresalmer et al 1992. The modification is in the use of the patella joint surface rather than maximum patella length as the denominator.**

### **The Patella Alta Index**

Leung et al (1996) studied the height of the patella in patients from Hong Kong. They evaluated 173 normal patellofemoral joints, 54 cases of anterior knee pain, 52 cases of patella dislocation and 11 cases of Osgood-Schlatter disease. He measured the height of the patella by the Insall, modified Insall, Blackburne, Caton-Deschamps and a further technique they called the “patella alta index”. They do not offer a rationale for creating this further technique which involves using the patella cartilage length as the denominator and sum of the patella tendon length and patella length as the numerator.

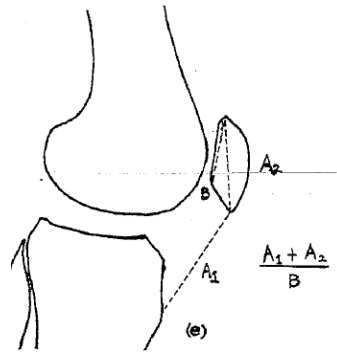


Figure 41. Patella Alta index. Image from Leung et al 1996. The ratio uses the patella cartilage length as the denominator and sum of the patella tendon length and patella length as the numerator

They found a statistically significant difference in the patella height between the southern Chinese population and the results reported by Insall in the western population. They found a definition of patella alta 15 to 20% higher in both the normal population and pathological groups. The mean ISR in the normal population was 1.17 (95% cut-off) in the southern Chinese population compared to 1.0 in the western population. However, they propose that as the Chinese population have a higher incidence of patellar instability (unreferenced by author) that the definition should not necessarily be adjusted as the higher position may be pathological even if the patient remains asymptomatic. Using the 95% cut off they were able to demonstrate significantly higher patellae in the dislocation and anterior knee pain group. They discuss the likelihood of the test not picking up pathology, describing the proportion of cases in the instability and anterior knee pain groups that are not above the 95% cut off.

Method	Insall-Salvati	Modified Insall-Salvati	Blackburne-Peel	De Carvalho (caton-Deschamps)	Patella Alta index
Possibility of misclassification	0.72	0.63	0.78	0.59	0.64

Table 12. Table reproduced from Leung et al 1996.

### Miller measurement

Miller et al evaluated the use of MRI imaging of patella height (Miller et al, 1996). They commented that whereas radiographs are taken with the knee at 30 degrees of flexion an MRI is performed in full extension. They sought to determine if the tendon being left “baggy”

in extension would have any effect on the apparent patella height. They also sought to describe a new technique on MRI where height was assessed in relation to the physal scar. They examined 46 knees and found that eight of them appeared to demonstrate a “baggy or wrinkled” tendon in extension, which implies that the tendon is not under tension and that its length cannot be measured in a straight line. They reported that there was no statistically significant effect on height. There was good correlation between the patella tendon/patella length ratio on radiograph at 30 degrees and MRI at zero degrees of flexion. Biedert later criticised Miller’s work as the physal scar is not consistently a marker of the limit of the articular cartilage.

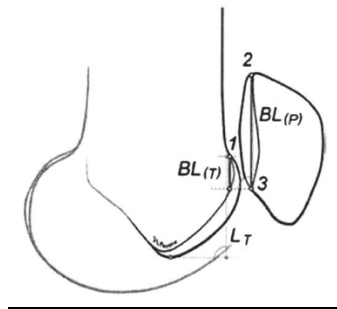
### **Patello-trochlear index**

The patellotrochlear index uses MRI to measure the overlap of cartilage between the trochlear and the femur (Biedert and Albrecht, 2006). It creates a ratio that uses the length of patella cartilage as the denominator and the length of the trochlear cartilage that is overlapped by the patella cartilage as the numerator.

Biedert and Albrecht evaluated the use of this ratio in 66 patients with meniscal pathology who were not known to have patellofemoral pathology. The mean patella-trochlear ratio was 31.7% (SD +/- 11.6, range -5 to 61%). Barnett et al (2009) looked at a number of patellofemoral indices in patients with known trochlear dysplasia. In 33 knees they evaluated the patella-trochlear index, the Caton-Deschamps index, the Insall-Salvati ratio and the Blackburne-Peel ratio. They found a weak correlation between the patellotrochlear index and the other indices. Unsurprisingly there was a strong correlation between the Caton-Deschamps and Blackburne-Peel ratio, there was a moderate correlation between the Insall-Salvati ratio and these. The patello-trochlear index in this group was 15.3% (SD +/- 17.1). The authors concluded that this index was significantly different to the others and probably more functionally relevant as it measured the actual cartilage contact between patella and femur.

The weakness of the patello-trochlea index is that it does not account for the mechanical advantages of an optimal patella height as it does not reference the centre of rotation of the knee in any way. The other weakness is that the index relies on the knee flexion position being constant across the scan images and between patients. In clinical practice tibio-femoral angle in the MRI scanner is subject not only to individual variations in patient flexibility and the set up of the scanner but is affected by body habitus. The femur being central within the thigh and the tibia anterior in the calf segment means that the bony relationships of the supine patient are subject to body habitus. If the knee is more flexed or extended then this will increase or reduce the ratio. As these pathologies frequently co-exist with hypermobility the knee is at

times significantly hyper-extended in the MRI scanner. As these potential confounders are not reported in the paper we may assume they have not been considered.



**Figure 42. Patello-trochlea index.** Image from Biedert et al 2006. The length of patella cartilage is the denominator and the length of the trochlear cartilage that is overlapped by the patella cartilage is the numerator.

### Patella engagement

Monk et al describe a similar measurement to Biedert. They described taking the “highest point of the articular surface” and then measuring the length of patella cartilage below this point and expressing it as a percentage of the total patella cartilage length. They refer to this as a measure of engagement into the trochlear sulcus. Many of these patients have trochlear dysplasia and in severe cases have no sulcus. Even in the normal trochlear the groove that defines the sulcus does not start at the most proximal point of the cartilage. The conclusions of the paper are that “surgery directed towards improving patella engagement should be considered”.

### Measurement of joint congruence

There is one validated technique that evaluates the congruence of the patellofemoral joint by Heino (Heino, 1999). The technique involved taking the MRI scan in the axial plane and measuring the width that articulates in each of the slices. The slices are 2-5 mm apart (depending on how they are set by the technician) and the technique makes the assumption that each slice maintains its width throughout. This method is a direct measurement of joint congruity. Although labour intensive and expensive it does permit an actual measure of congruity rather than an inferred measure. The method was validated by Heino and Powers via a cadaveric study, the authors undertook a measure of joint congruence at differing positions of flexion in a cadaver by use of digital contact pressure paper. I was able to contact Dr. Powers

in California and he was kind enough to provide me with details of their protocols. They then used the MRI technique and found excellent correlation between the two. The application of the technique is described in further detail in the methods section and will form the primary outcome of this study.

### **Choice of outcome measure**

Abnormalities of patellofemoral anatomy has been described in a precise and quantitative manner through multiple previous patellofemoral indices. A near exhaustive description of these is found in the previous pages.

The indices fall into the category of those that assign a cause to the patellofemoral abnormality and those that quantify the abnormality of the articulation. This study aims to evaluate the presence of incongruity at different knee positions and then the effect of surgery on the congruity of the joint; therefore a measure of congruence is required. The only described direct measurement that can be made in the awake person is described by Heino et al.

### **Measurement tools:**

Previous investigators have used Computed tomography (CT) scans, magnetic resonance imaging (MRI) scans, ultrasound and three-dimensional navigation techniques to describe joint anatomy, movements and congruence. The investigator considered each of these techniques for assessing joint congruence.

### **Plain radiographs**

Patella height is most often measured on a lateral radiograph. Patella and trochlea morphology and their relations to one another have been described on an axial radiograph. This image relies on the knee being flexed and the radiographic beam passing from superior to inferior through the trochlear. The image has been produced by several different methods. The method most commonly used in hospitals was first described by Merchant in 1974 and still carries his name, the “Merchant view” . The major limitations of plain radiographs are that they do not image the cartilage and that they do not provide any axial data that can be used to quantify cartilage contact. Although they produce an apparent profile of the trochlea they in fact only demonstrate the part of the trochlea that is perpendicular to the radiograph beam. As the trochlea is curved it only represents one small part of the trochlea.

Radiographs do have several very significant advantages, they have a low financial burden, they impart little radiation, they are used on a regular basis by clinicians and they are readily available.

## Ultrasound

Ultrasound has been used by Øye et al (2014 and 2015) to evaluate the shape of the femoral trochlea and the patella in neonates. Øye et al clearly defined the shape of the femoral trochlea and the patella, they accurately measured the sulcus angle and the trochlea index in 174 neonates. The device and process is not harmful and is inexpensive to run. I experimented with the technique but found that it could not be as effectively reproduced in the adult. Whereas the neonatal knee is primarily cartilaginous the adult knee architecture is bony and the view available of the interface between patella and trochlea was only visible at 30 degrees of flexion from a trans-patella tendon view.

Ultrasound has been previously used by Shih and Amis (2003) to examine patellofemoral tracking. Those investigators utilised a medical ultrasound device mounted on a brace on the lateral side of the thigh and calf. The device measured the proximity of the patella to the transducer in different positions of flexion.

I visited Professor Andrew Amis in his laboratory at Imperial College, London to evaluate the technique. I reviewed the published data from Professor Amis(Shih et al, 2003). Although a convenient clinical tool the technique had two limitations that precluded its use. The device could not be reliably set up for comparison between before and after surgery and there was a 4mm margin for error. The major limitation was that the device could not measure the congruence of the joint, only the relative laterality of the patella. Although an novel and interesting technique I did not believe I could use it to reliably detect and record subtle differences when the two measurements are made several months apart.

## Three-dimensional computer navigation

Belleman's group described a technique where three dimensional infra-red reflecting markers would be drilled onto the femur, tibia and patella and then the knee mapped with a CT scanner to assess the precise location of the pins in relation to the trochlea groove (Victor et al, 2009). The knee could then be cycled in front of the infra-red camera and the precise relation of the patella to the trochlea would be known. Although the technique was considered useful in their cadaver study it does present some problems when used in the patient population. The process of drilling introduces the risk of iatrogenic bone infection. Additionally, the process of drilling the pins into the bone would require a general anaesthetic. Although this may be achievable at the peri-operative evaluation it would mean an additional anaesthetic for the post-operative follow-up scan which was deemed unacceptable.



## CT

CT scanning relies on ionising radiation, although modern scanners use comparatively little radiation. The harm from radiation is linear in large populations but stochastic for an individual. The consensus in the nuclear energy industry in the European union is that cancer risk may be increased in a linear fashion at a rate of 5.5% per sievert. The consensus in the nuclear energy and healthcare industries is that workers should not be exposed to over 20msv per year (McLean et al, 2017). Annual background radiation is approximately 2.5msv, applied in a uniform pattern to the entire body (McLean et al, 2017). The amount of radiation imparted by a CT scan is dependent on the volume and density of the tissues being scanned and as such the peripheries attain a lower dose than the trunk. It is reasonable to anticipate that a knee examination would impart less than the 0.16 msv (Biswas et al, 2009).

Body region undergoing CT scan	MSV
Head	2.0
Neck	3.0
Chest (Standard)	7.0
Chest (R/O pulmonary embolism)	15.0
Abdomen	8.0
Pelvis	6.0

**Table 13. Doses in Radiology and Diagnostic Nuclear Medicine, Mettler et al 2008.**

The figures quoted are for a single static CT scan. This study intended to perform dynamic examination, where the scan is repeated over the course of limb movement (up to five times) with a further three passive examinations at differing position of flexion (0,20 and 40 degrees). These were performed before and after surgery All scans would be performed before and after surgery. A worst-case scenario of 2.56 msv can be calculated (0.16msv x 2 pre & post op x 8 scan positions).

The total dose is below the 20msv annual dose threshold. For a patient receiving medical treatment and for a person in the workplace the convention of 20msv per year may be considered acceptable. However, in a research project where there is no direct benefit to the patient the investigators considered any such risk to be unacceptable. Additionally, we must be aware that repeated CT scanning may be unacceptable to many patients and deter enrolment.

## **MRI**

As with CT scanning MRI scanning permits assessment of anatomy in the axial, coronal and sagittal plan but can be oriented to any anatomical axis. Magnetic Resonance Imaging is a non-destructive technique. It involves no use of ionising radiation. It does generate a significant magnetic field so may be dangerous to persons with intracerebral metal clips, intraocular metal artefact, pacemakers or newly placed metallic cardiac stents. The images produced by the technique provide images of the cartilage as well as the bone, permitting more accurate calculation of congruence than CT scanning.

I selected MRI as the data collection tool as it is a safe technique that provides precise data regarding cartilage on cartilage contact. The most significant factor that led to my choice of MRI as measurement tool is that it was used by Heino et al when validating their technique for measuring joint congruence (Heino, 1999).

## **Methods of activating the quadriceps**

Part of my stated objective was to reproduce the conditions of ambulation as far as possible. In order to do so I considered several described techniques including using a specialist vertical weightbearing scanner and stimulating the muscles of ambulation as far as possible. As the patellofemoral joint is part of the quadriceps extensor mechanism it is activity in that muscle that forms our primary focus.

Several methods of loading the quadriceps have been described including a weight-bearing MRI at different positions of flexion (Powers et al, 1998), supine stimulation of the quadriceps by the patient suspending the heels off the scanner bed (Martinez et al, 1983) and by resisted extension in the supine patient against a deflating balloon (McNally et al, 2000). I decided to investigate the technique involving the deflating balloon and so contacted McNally in Oxford. I was able to organise a visit and review the protocols in use in Oxford. I used these as a basis for developing my own protocols for this study. Ultimately I decided to simultaneously gather data with the knee resting in different position and with the knee extending against resistance.

## Chapter 2b: A study of the congruence of the unstable joint

### Hypotheses

- The unstable patellofemoral joint is less congruent than the normal patellofemoral joint throughout knee movement.

Secondary hypotheses:

- The unstable patellofemoral joint is less congruent when the knee is extended.
- The congruence of the patellofemoral joint is increased by patella stabilisation surgery.

### Methods

#### Research participants

The experimental subjects were recruited from the patient waiting list for surgery at the Avon Orthopaedic Centre, Southmead Hospital, North Bristol NHS Trust. 31 subjects took part in this research study, 12 were male and 19 were female. The study also utilised a control group. This control group was selected not as an alternative therapy, but to define normal values and validate the study methodology. For this normal control group nine healthy volunteers were recruited from the hospital staff, all volunteers were screened by asking if they had any history of knee trauma, knee pain or patella dislocation and following scan the images were checked for any sign of chronic disease. No exclusion were made. Of the nine controls seven of these were male and two were female. Mean age amongst the experimental group was 25 (range 16-42) and amongst the normal knee group 25 (19-31).

Patients were identified from the list of patients awaiting surgery for patella stabilisation. Inclusion required a history of at least two patient reported episodes of patellar instability with ongoing experience of discomfort or distrust in knee. Patients were excluded if they were unable to provide valid consent, unwilling to participate, aged less than 17 years, suffered degenerative knee joint disease (any radiographic evidence of osteoarthritis), were pregnant, if there was a history of metal objects or the possibility of metal object in soft tissues, particularly brain, eye, heart, spinal cord or if they were unreachable by phone.

A total of 60 patients who were approached were not included, the inclusion rate was 33%. The reason for exclusion are shown in figure 43.

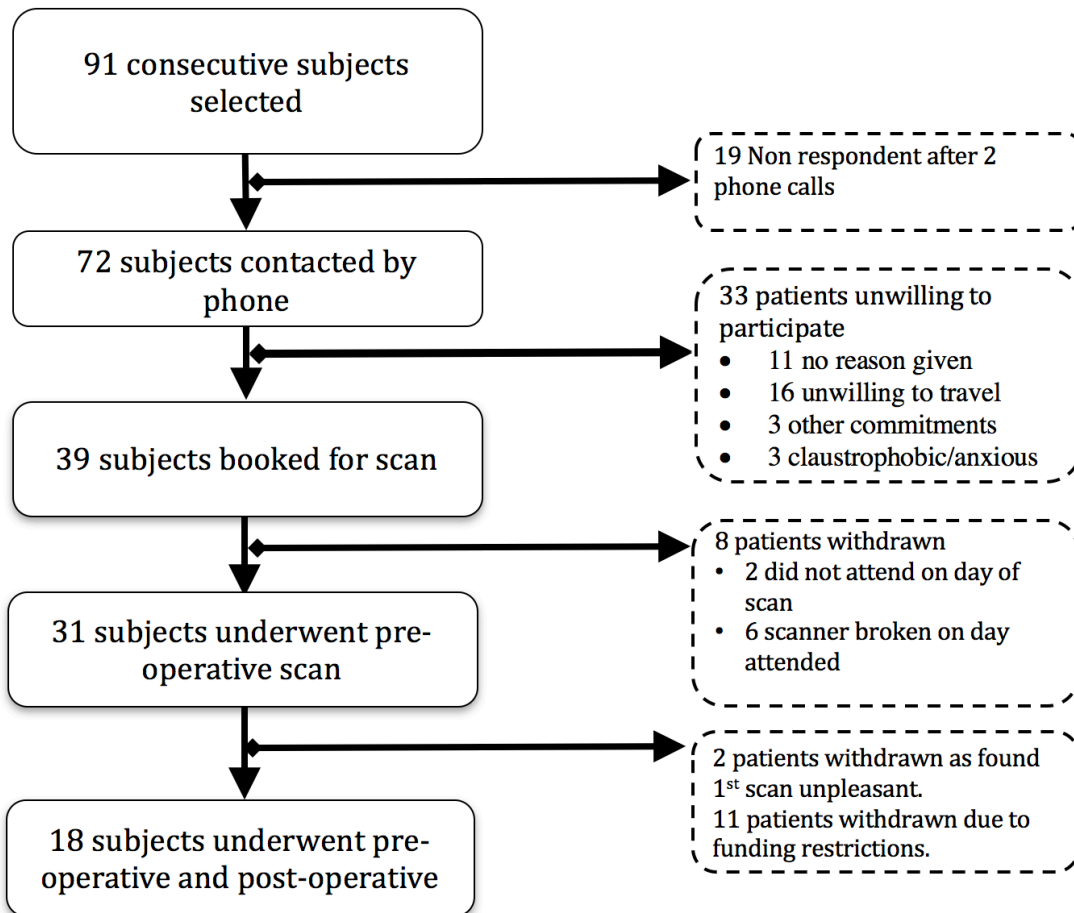


Figure 43. Flow chart of subject inclusions and exclusions.

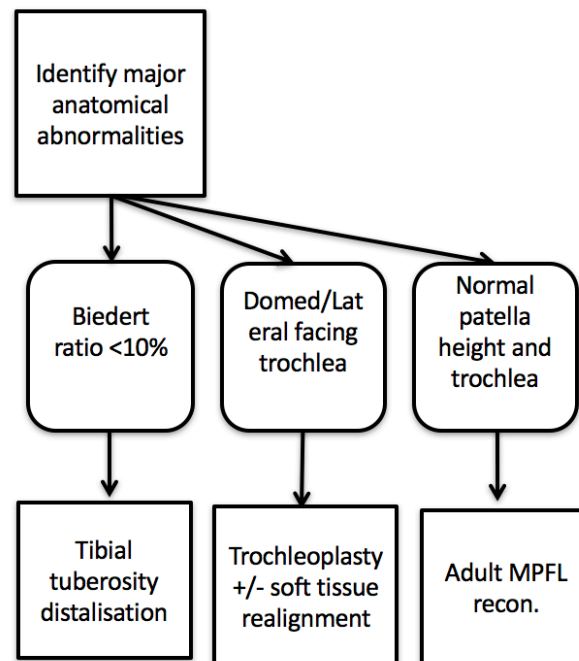
### Recruitment

The waiting list of Mr Jonathan Eldridge was screened by the investigator in August 2012. Patients who were currently on the waiting list for trochleoplasty, MPFL reconstruction, tibial tuberosity transfer or any combination of those procedures were identified. Patients that met the screening criteria were telephoned by the investigator who gave details of the study to patients who expressed an interest in participation. Reasons for non-participation, where given, were recorded.

Patients who expressed an interest in participation were offered an appointment to meet the investigator following their pre-operative assessment clinic at which time written information and further explanation of the study was provided. If the patient still wished to participate, consent for enrolment in the study was obtained. Patients underwent MRI evaluation before surgery and were offered further evaluation 1 year after surgery.

Subjects were assigned surgical groups by the surgical team based on the characteristic abnormality causing instability. The anatomical aetiology of the instability as defined by the findings of a routine pre-operative static MRI in full knee extension. The flowchart below

illustrates how decision is influenced by the standard pre-operative imaging findings. The dynamic MRI used in this study was not part of the standard work up and did not influence the surgical decision making.



**Figure 44. The anatomic approach to surgical indications in patellofemoral instability surgery. The most severe pathology is identified.**

Patients were offered participation in the MRI section of the study and were also offered enrolment in the gait study (see next chapter). No financial inducement or recompense was offered, patients were required to pay all costs of attending including transportation and parking if they chose to participate.

### **MRI Data collection**

MRI analysis of patellofemoral congruence: MRI was performed with a GE Discovery MR450 scanner and an eight-channel cardiac coil. The subjects were advised to expect a pre-operative MRI appointment and a post-operative MRI appointment, where patients agreed to also take part in the gait study they were also advised of the location of these appointments. In order to maximise recruitment, the subjects were asked what time of day would most suit them and then the appointment that was most convenient was offered to them. The patients arrived at the MRI suite and were met by the investigator. The subject underwent a standard checklist

where they were asked specific questions regarding comfort and safety in the MRI scanner. The checklist is a requirement of the Radiology department.

Have you had an MRI before?

Have you had any operation with your head/ears/brain?

Have you had any operations on your spine?

Have you had any operations on your chest or heart?

Have you had any operations using metal clips or pins?

Do you have a cardiac pace maker?

Do you have any aneurysm clips in situ?

Is there any chance that you may be pregnant?

Is there any possibility that there may be metal in your eye?

Have you ever had a bullet or shrapnel injury?

Are you wearing a cardiac/hrt/nicotine patch?

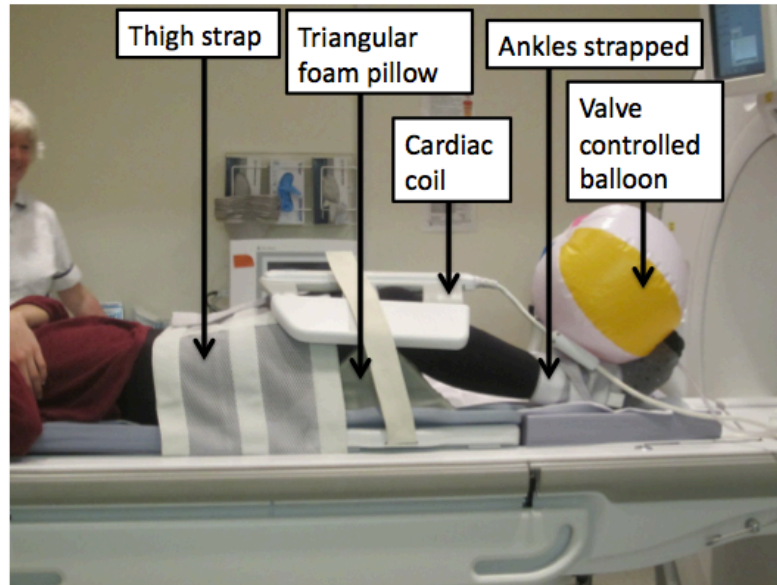
Do you experience claustrophobia?

**Table 14. Safety questionnaire for MRI scan.**

All metallic jewellery was removed. The subject lay supine on the MRI table with a triangular wedge under the knee and a strap over the thighs in order to maintain the position of the femur as still as possible. The ankles were strapped together so that the knees were permitted to extend whilst the thigh remained still. Data was captured in both static and quadriceps active mode.

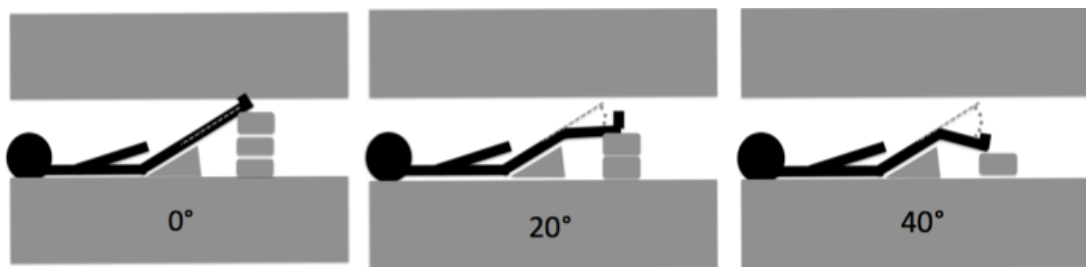
### **Patient positioning**

The initial localiser MRI sequence performed was an ultrafast gradient echo 3 plane localiser. The localiser scan permitted the technician to identify the boundaries of the trochlea and plan the location of the definitive quality scan. The scan boundaries were placed beyond the boundaries of the trochlea. Blocks of axial images were captured with one sagittal to calculate the precise knee flexion position. The image was centred over the trochlea and then as the knee extended the patella came into view, maintaining all the time the same series of images of the trochlea.



**Figure 45. Patient positioning within the MRI scanner.**

Static: The patient was secured as above and the knee permitted to rest at 40 degrees of flexion, a series of images was captured. A further foam cushion was placed under the heel to attain a scan at 20 degrees of flexion, finally a further cushion was placed to attain a scan 0 degrees of flexion and the series repeated again.



**Figure 46. Patient positioning, passive. Block are sequentially removed to standardize knee flexion. Scan aiming for approximately 0,20,40 degrees, actual knee position measure from MRI scan.**

Quadriceps active: The patient was positioned supine with a triangular foam pillow under the knee. A beach ball was placed anterior to the tibia with a valve under the control of the subject. The subject was requested to extend the knee, pushing the lower leg against the balloon, causing it to deflate. Subjects were advised that it would be expected to take two minutes to achieve this. The MRI operator informed the subject that the scan was due to start so as to coincide this with the beginning of the scan. As the knee extended the scan was begun and repeated whilst the subject deflated the balloon.

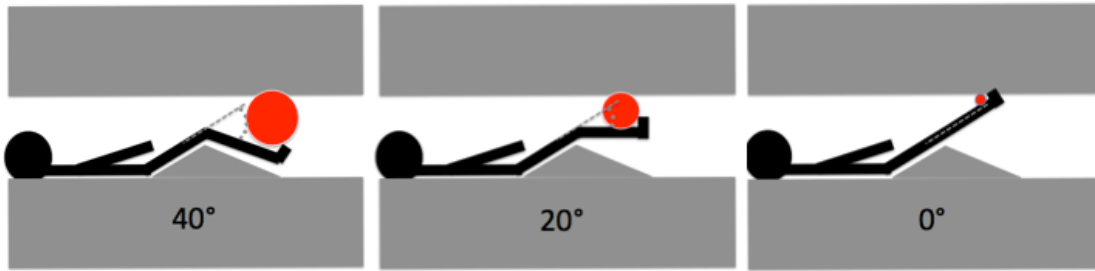


Figure 47. Patient positioning in MRI for active quadriceps scan. Balloon deflates against resistance and scan repeated during deflation. Scan aiming for approximately 0,20,40 degrees, actual knee position measure from MRI scan.

Rapid sequence axial images were captured whilst the ball was permitted to continue to deflate under the patient's control. The deflation rate was dependent upon the exertion of the patient and was not controlled. Five to eight sequences were captured per deflation. The subject had the opportunity to abort the scan if they felt it to be painful or claustrophobic via a continuous audio feed with the scan operator.

#### Image sequence

As discussed above a localiser scan (ultrafast gradient echo 3 plane localiser) was performed so that image collection could be planned. The localiser provides a low-quality series of images that enable the operator to place a grid for planning of the axial images.

After the localiser scan located the distal femur, the sequence placement was planned so that the entire trochlea could be imaged. In both the active and passive modes the thigh did not move and it was possible to attain adequate quality imaging of the trochlea, without motion artefact. In each sequence images captured included one sagittal slice and 10-18 axial slices (dependent on patient size) at 5mm intervals.



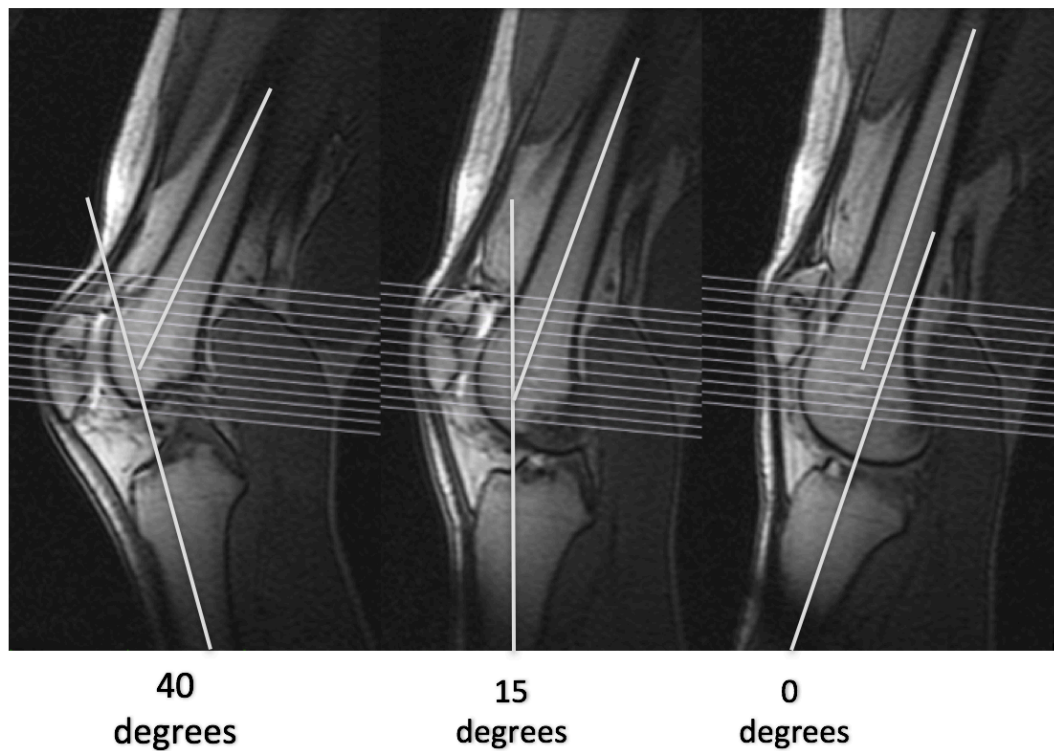


Figure 48. Example of three different sagittal slices, sequences at 0,20 and 40 degrees. Tibio-femoral angle measured.

In any given scan, up to 5 images demonstrate contact between the patella and the trochlea and at any given moment, the entire trochlea was captured in order to ensure all the relevant images along the path of the patella were captured.

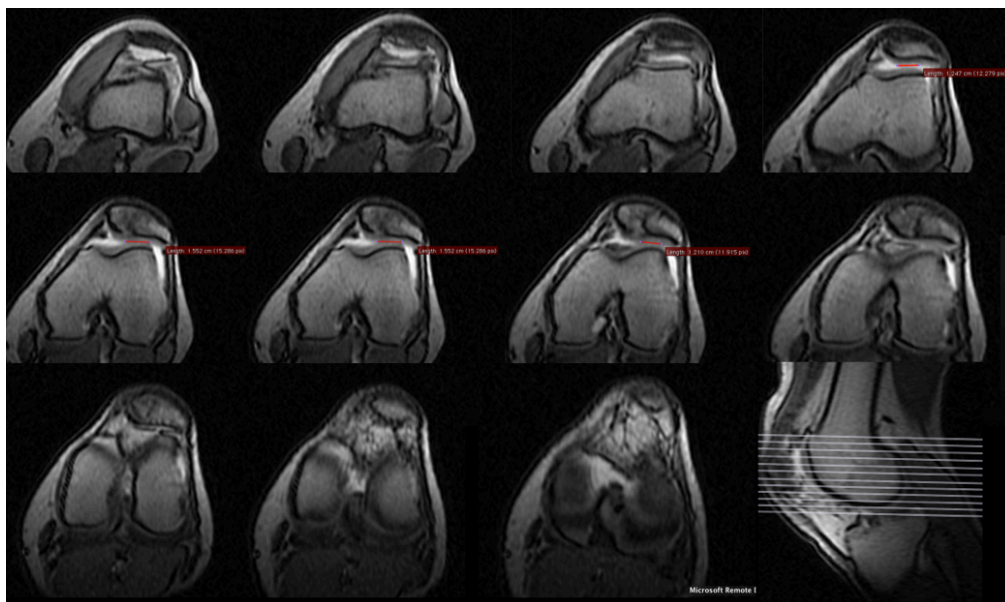
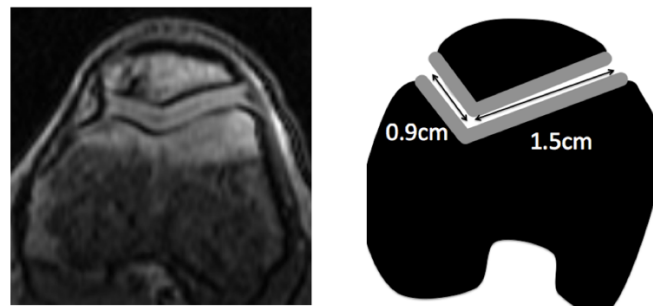


Figure 49. One complete image sequence including 11 axial and one sagittal image.

### Interpretation of scan images

Congruence measure: All of the MRI and x-ray images were interpreted by the primary investigator. The technique is an adaptation of that made by Heino et al as per the literature review. The objective was to ascertain the area of contact between the patella and the trochlea. The joint plane is largely coronal, however capturing the entire joint in the coronal plane is not possible as it is curved in both the coronal and sagittal planes. Even if it were perfectly flat and only in one place it would require an exact slice to capture the articulation. It is more accurate and reproducible to capture a plane perpendicular to this and examine slices of the articulation individually. This gives a precise measure of the length of the articulation but not of the width. The width of each slice is known as each slice is 5mm apart. Examining the lengths of the medial and lateral facets separately permits a conceptual flattening of the joint surface.



**Figure 50. Measurement of overlap. On the left that actual image that is used more measurement. The image on the right is for illustrative purposes only.**

During the dynamic imaging, multiple sequences were captured. The knee position was measured on the MRI Sagittal image associated with each set of axial images. Using digital data supplied by the institutional PACS (GE Healthcare Centricity™ & Fujifilm Synapse™) the operator manually identified boundaries of cartilage contact between the patella and femur on both sides of the trochlear sulcus on the axial view.

These measurements were recorded as linear distances. Each slice is 5mm wide and the surface area of each slice was calculated by multiplying the length by 5mm. Each slice surface is then summed to reach a measure of the surface area in contact between the two bones to give a measure of congruency between the articulating surfaces in each measurement condition.

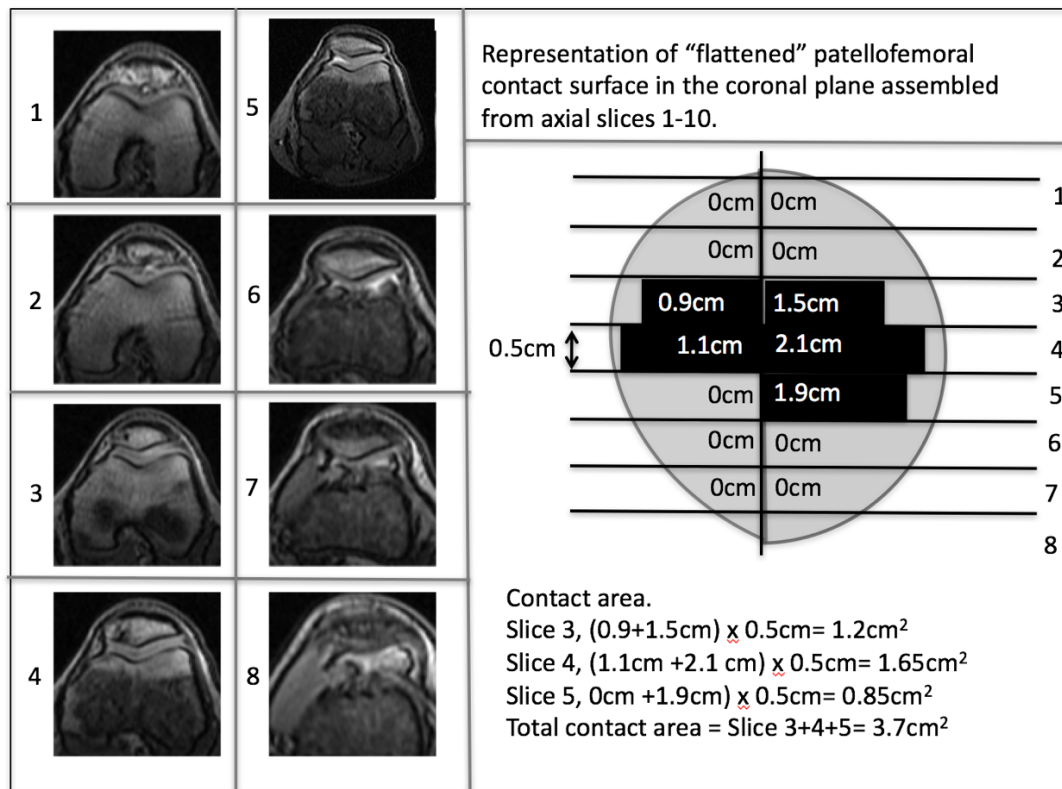


Figure 51. “Flattening” of axial imaging. Slices are at 5mm intervals. The width of each slice in which there is contact between femur and patella cartilage is multiplied by 5mm. Each measurement is then summed to give a total are of congruence.

### Handling of repeated and missing data

Subjects extended their knees at different rates. Sometimes a subject might present with multiple data points at a similar position of knee flexion. Some subjects found it difficult to attain the final degrees of extension. In some cases, the subject extended their knee so quickly that some ranges were not captured. Where data was missing the data point was left blank. The missing data is not missing at random by knee position. The best represented data was that in the 0-20 degree range. The poorest was at the extremes of range.

To avoid a bias where some subject disproportionately represented a position by presenting multiple data points in one position a limit of one data point was placed on each patient for inclusion in each 10-degree range. The most central data point within each 10-degree range was selected. For example, in the data set below the raw data would be converted thus:

Data available	Most central data selected	Utilised date
<ul style="list-style-type: none"> <li>• 0 cm<sup>2</sup> at -5 degrees.</li> <li>• 0.5 cm<sup>2</sup> at 0 degrees.</li> <li>• 0.6 cm<sup>2</sup> at 2 degrees.</li> <li>• 0.6 cm<sup>2</sup> at 5 degrees.</li> <li>• 3 cm<sup>2</sup> at 11 degrees.</li> <li>• 3.2 cm<sup>2</sup> at 25 degrees.</li> <li>• 3.3 cm<sup>2</sup> at 29 degrees.</li> <li>• 4.1 cm<sup>2</sup> at 34 degrees.</li> </ul>	<ul style="list-style-type: none"> <li>• 0 cm<sup>2</sup> at -5 degrees.</li> <li>• <del>0.5 cm<sup>2</sup> at 0 degrees.</del></li> <li>• <del>0.6 cm<sup>2</sup> at 2 degrees.</del></li> <li>• 0.6 cm<sup>2</sup> at 5 degrees.</li> <li>• 3 cm<sup>2</sup> at 11 degrees.</li> <li>• 3.2 cm<sup>2</sup> at 25 degrees.</li> <li>• <del>3.3 cm<sup>2</sup> at 29 degrees.</del></li> <li>• 4.1 cm<sup>2</sup> at 34 degrees.</li> </ul>	<ul style="list-style-type: none"> <li>• 0 cm<sup>2</sup> at -5 degrees.</li> <li>• 0.6 cm<sup>2</sup> at 5 degrees.</li> <li>• 3 cm<sup>2</sup> at 11 degrees.</li> <li>• 3.2 cm<sup>2</sup> at 25 degrees.</li> <li>• 4.1 cm<sup>2</sup> at 34 degrees.</li> </ul>

**Table 15.** Example of datum to selection to most central in angle range. For illustrative purposes only. Working from the left column to right we can observe how the most central point in each range is selected. In doing so each patient only provides one data point in each range and the P value is not artificially lowered in the final analysis.

### Sample size

The sample size was constrained by financial limitations, regardless an a-priori power calculation was performed. Accepting that there are no equivalent studies on the literature I estimated a medium to large effect of surgery to outcomes. The sample size was based on a two sample independent t-test with a mean difference of 2cm<sup>2</sup> with equal standard deviation of 1.75, power of 80%, and type I error=0.05 with a sampling ratio of 3:1 (case:controls) yielding 27 cases and 9 controls. Power calculation performed using G-Power (Faul et al, 2007).

### Other data

Other data such as patient demographic data, weigh, height, hypermobility score, frequency of patella dislocation and previous surgery was attained by review of the patients records.

The other co-variants included anatomic measurements that were also made on the MRI scan. These measures have been described in literature review and include the tibial tuberosity to trochlea groove offset, the Biedert ratio and the Dejour grade.

Patients underwent one of three different operations including trochleoplasty, tibial tuberosity distalisation, medial patellofemoral ligament reconstruction or combinations thereof. Patients were assigned to group “dysplasia” where the groove was absent, replaced

by a bump or the lateral facet faced laterally. Patients were assigned to the group “Alta” where the Biedert ratio was less than 0.1 (Biedert and Albrecht, 2006). Patients underwent medial patellofemoral ligament reconstruction when the patella height and the trochlea was otherwise normal. All subjects in the study underwent surgery. Trochleoplasty was performed in ten cases, tibial tuberosity distalisation in eight cases, MPFL reconstruction in nine cases and combined MPFL and tibial tuberosity distalisation in four cases.

### **Statistical plan**

Descriptive statistics will be illustrated in a table, scatter plot will be used to evaluate the gross distribution of static and quadriceps active data. The quadriceps active data can be expected to be more physiologically representative. If the quadriceps data is not erratic (due to muscle contraction) in comparison to the resting knee data we will use that data for the analysis.

Comparison will be made between the normal & preoperative data and the pre & postoperative data and the simple T-tests. Histograms will be utilised to illustrate trends in congruence during knee flexion.

## Results

### Descriptive statistics

Descriptive results are presented in the tables below. Between the cases and normal controls the ages are well balanced. The mean age was 25 in the case group and 26 in the controls. The sexes do not match well however with 61% of the cases female and 22% of the controls being female. Though the laterality is probably less important this is well balanced in both groups, 36% being left amongst the cases and 44% amongst the controls. The other co-variables that are associated with the pathology such as increased tuberosity offset (TTTG), patella alta (ISR), Hypermobility (Biedert score), trochlea dysplasia (Dejour A-D) are more frequently present amongst the cases than the controls. None of the controls have experienced a previous dislocation (this was an inclusion criteria for the controls). Most of the cases have had more than 2 dislocations. 7 of the cases have had a previous surgery of the patellofemoral joint.

	Cases						Controls					
	Mean	SD	P25	P50	P75	n	Mean	SD	P25	P50	P75	n
Age (years)	25	6.9	20.2	24	28.6	31	26	5.1	21	28	29	9
TTTG (mm)	13.3	4.6	9.5	14.0	16.3	31	11.9	3.20	9.0	12.0	15.0	9
ISR (ratio)	1.37	.20	1.2	1.4	1.5	31	1.19	0.09	1.15	1.23	1.25	9
Biedert (score)	32.5	23.0	19.6	25.0	46.7	31	38.2	3.3	35.5	39.4	40.5	9
Age 1 <sup>st</sup> dislocation (years)	14.9	3.8	12.0	15.0	16.0	21	-	-	-	-	-	9

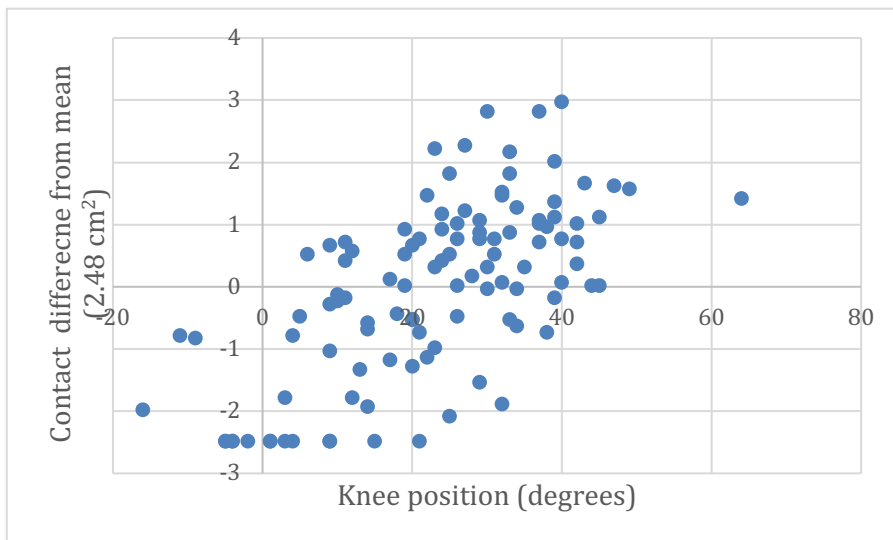
Table 16. Subject characteristics continuous data.

	Cases		Control	
	n	%	n	%
Sex (female - male)	19 - 12	61 female	2-7	22.2 female
Laterality (left - Right)	11 - 20	36 left	4-5	44 left
Dejour grade	Normal	6	19	100
	A	3	10	0
	B	5	16	0
	C	14	45	0
	D	3	10	0
Hypermobile (Beighton score of 4+)	7/31	22.6	0/9	0
Previous surgery	7/31	22.6	0/9	0
Subjects with >2 dislocations	19/31	61	0/9	0

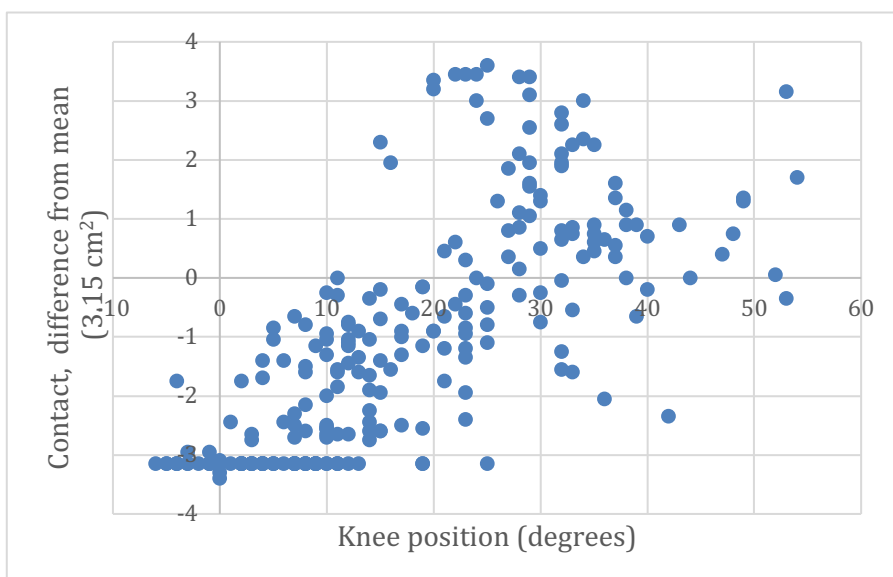
Table 17. Subject characteristics ordinal data.

### Scatter plot of all data

The data prior to removal of duplicates is displayed below as a scatterplot of the difference from the mean for both quadriceps active and passive data. The floor effect of zero congruence is observed in greater effect in the quadriceps active chart as a solid line at  $-ve$  3.15. This gives us some clue as to the distribution of the data. In each graph the mean is the mean of all the data of those patients. In the case of the passive knee this is  $2.48\text{cm}^2$  and in the case of the quadriceps active  $3.15\text{cm}^2$ . A clear trend can be observed towards increasing congruence as the knee is flexed. For this reason the subsequent data is partitioned- so that data within specific ranges can be represented.



**Figure 52. Scatter plot passive knee. Difference from mean. Each dot represents one patient. A trend of increased contact with increased knee flexion is observed.**



**Figure 53. Scatter plot quadriceps active knee. Difference from mean. Each dot represents one patient. A trend of increased contact with increased knee flexion is observed.**

### Bias due to removing repeated data

As the range in which the scan was not controlled it was possible that some patients would have more than one measurement in a specific range and therefore be over represented in that range. Therefore repeated data was removed (as described in methods by selecting the most central in each range). To determine what effect this may have, i.e. if it was removed with a systematic bias, an independent t-test of the means was performed. The table below illustrates no significant difference between the mean prior to and after removal of duplicated data.

Independent sample T-test.	n	Mean joint congruence cm2	mean diff	95% lower	95% upper	P
All	246	2.07	-0.11	-0.54	0.32	0.625
Selected data	110	2.17				

**Table 18. Independent T-test. All data vs utilized data.**

There was no significant correlation between completeness of data and any of the demographic, anatomic or historical features (greatest was Pearson's K -0.331 comparing completeness to age).

### Choice of primary outcome measure. Quadriceps active vs passive

The remainder of the results present the quadriceps active results for several reasons. The data is more complete in the quadriceps active data set with 110 data points than the quadriceps passive data set which has 75 data points. The differences can be visual inspection on the scatter plot and demonstrate a floor effect that is more evident in the quadriceps active group.

The overall direction of the association appears to be similar. We can reasonably expect the results in the quadriceps knee to be more representative of the knee during gait.

	Active quadriceps						Passive knee					
	n	Mean joint congruence cm2	SD	P25	P50	P75	n	Mean joint congruence cm2	SD	P25	P50	P75
<0	7	0.029	0.76	0	0	0	8	0.48	0.76	0	0	1.36
0-10	26	0.59	0.86	0	0	1.19	12	0.92	1.09	0	0.35	1.92
11-20	26	1.73	1.24	0.587	1.78	2.59	15	1.80	0.99	1.15	1.90	2.60
21-30	24	3.13	1.33	2.40	3.18	3.99	22	2.90	1.17	1.93	3.12	3.66
31-40	18	3.85	1.16	3.14	3.88	4.65	20	3.25	1.15	2.48	3.30	3.90
40+	9	3.77	1.51	3.13	3.88	4.65	7	3.42	0.70	2.50	3.60	4.10
Combined	110	2.17	1.76	0.40	2.15	3.56	84	2.31	1.45	1.23	2.50	3.40

**Table 19. Mean joint contact (cm2). Descriptive statistics. Active quadriceps and passive knee.**



## The unstable patellofemoral joint is less congruent than the normal patellofemoral joint throughout knee movement

The distribution of the pre-operative quadriceps active data was first evaluated. The floor effect of the zero congruence (i.e. when the joint is completely incongruent) results in skewness (0.842) of the data. This natural boundary is observed in the histogram. Shapiro-Wilk test confirms that the congruence was not normally distributed ( $P < 0.000$ , skewness 0.842, kurtosis 1.683).

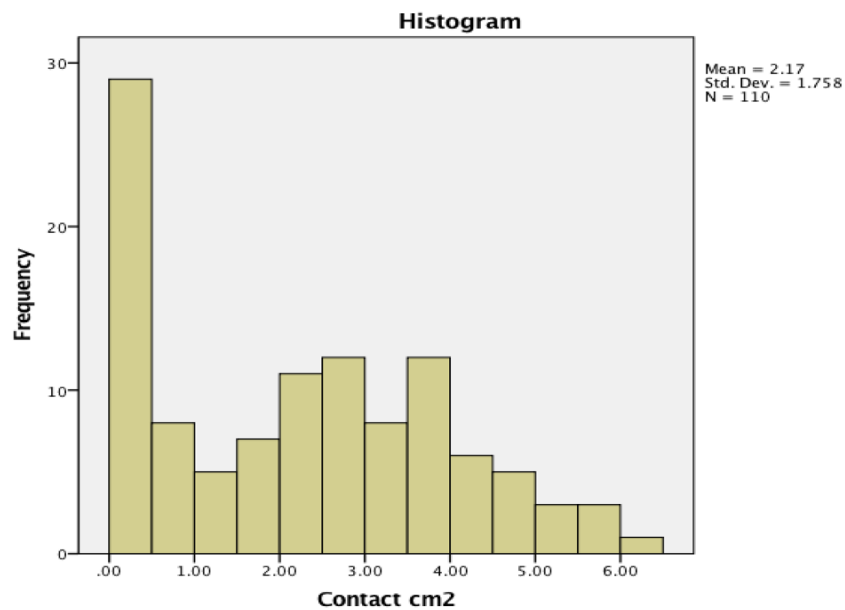


Figure 54. Histogram demonstrating the skewness of the quadriceps active contact data.

Quadriceps active: knee position.		n	Mean joint congruence cm2	mean diff	95% lower	95% upper	P
<0	Case	7	0.029	0.029	-0.10	0.16	0.626
	Control	2	0.00				
0-10	Case	26	0.59	-1.09	-1.80	-0.38	0.004
	Control	11	1.68				
11-20	Case	26	1.73	-2.22	-3.16	-1.27	0.000
	Control	9	4.00				
21-30	Case	24	3.13	-1.57	-2.64	-0.49	0.006
	Control	8	4.70				
31-40	Case	18	3.85	-1.44	2.58	-0.30	0.016
	Control	5	5.29				
40+	Case	9	3.77	-0.83	-4.51	2.85	0.618
	Control	1	4.60				
Combined	Case	110	2.17	-1.24	-1.91	-0.55	0.000
	Control	36	3.40				

Table 20. Mean joint contact (cm2) cases and controls, independent sample T-test.

The greatest differences in congruence between the controls and the cases are in the range of zero to twenty degrees. The greatest mean differences and greatest statistical significance is at the 11-20 range. The histogram illustrates the trend from incongruence to congruent as the knee flexes. The curves match well between controls and cases; the exception is at the 40+ range where there only one case has been recorded and the trend for increased congruence is not observed.

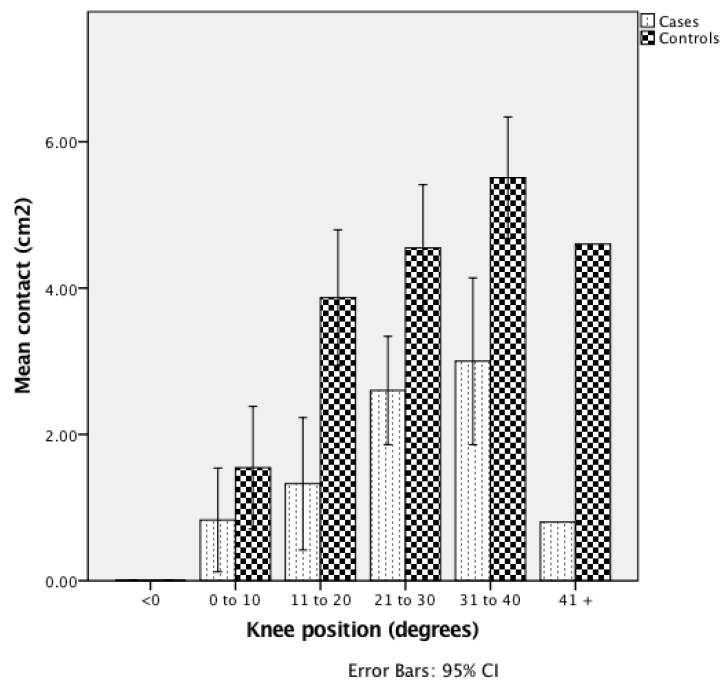


Figure 55. Histogram of congruence at different knee positions. Cases and controls.

### Pre-operative vs Post-operative

18 patients completed both the pre-operative and the post-operative scans. Small numbers for this part of the study mean that cautious interpretation of results is required. Although increased contact is observed in all knee positions the differences only meet significance at the 11-20 range.

Knee position (degrees)	Pre-operative			Post-operative			Paired T-test result			
	n	Mean joint congruence cm2	SD	n	Mean joint congruence cm2	SD	Paired MD	95% lower	95% upper	p
<0	0	-	-	0	-	-	-	-	-	-
0-10	14	.69	0.85	14	1.37	1.28	-0.68	-1.44	0.07	0.07
11-20	18	2.03	1.23	18	3.20	1.77	-1.17	-1.92	-0.42	0.004
21-30	11	2.60	1.61	11	3.61	2.08	-1.02	-2.46	0.42	0.147
31-40	8	3.72	1.68	8	4.57	0.97	-0.85	-2.85	1.15	0.348
41+	1	3.15	-	1	4.40	-	-	-	-	-
Combined	52	2.07	1.62	52	3.03	1.93	-0.96	-1.44	-0.49	0.000

**Table 21. Mean joint contact (cm<sup>2</sup>) pre-operative vs post-operative. Paired T-Tests at differing knee positions.**

### **Repeatability of measure (MRI image measurements)**

The repeatability of the measurements of MRI congruity were assessed by Pearson's correlation coefficient in a small proportion of patients. Due to cost restriction the repeatability of the scan was only measured in three of the of the patients. Scan being repeated at one month post first scan in each case. Intraobserver error was highly correlated (Pearson's 0.892).

The measurements were repeated for the primary investigator to give a measure of intraobserver error of reading the scans only. This data collection is labour intensive and this was performed in 12 of the patients. The measurements were repeated by another observer (HC) for assessment of interobserver error. Measures were made 12 months apart, when the research assistant began working with the primary investigator. Measures were highly correlated for intra-observer error (Pearson's 0.985) and for interobserver error (Pearson's 0.910).

## **Discussion**

### **Strengths and weakness of study design**

The study aimed to characterise the congruence of the patellofemoral joint during knee movement in the normal and pathological conditions and to discover if stabilising the knee cap also increases the contact between the femur and the patella. The study aimed to determine if congruence increases after surgery. An increased surface area of contact between the patella and trochlea cartilage with the same force imparted may be expected to reduce pressure on that cartilage.

Designs considered included:

1. Experimental study with randomisation.
2. Observational study
3. Quasi-experimental study.

#### **Observational**

Several observational study designs were considered including a cross-sectional study. A cross-sectional study could provide information on patellofemoral congruence of patients with instability or the patellofemoral congruence of patients after surgery. However, they would not evaluate the effect of surgery on congruence.

#### **Randomised Study design**

Randomisation is a powerful factor for demonstrating correlation or causation. Study designs that demonstrate causation frequently rely on randomisation. An experimental design such as a randomised controlled trial could evaluate the effect of surgery. This would involve randomising patients with patellar instability to surgery and some to no surgery and then evaluating the effect on the change in patellofemoral congruence over time. This study design though robust would be time consuming and costly. In order to justify a study such as this a stronger initial evidence base is required. At the current time, it would be hard to establish equipoise when the outcome of patellofemoral incongruence is considered. It may be an avenue for future work.

#### Quasi-experimental

A before-after quasi experimental design lacks the element of randomisation and much of the control of the investigator is lost (Gribbons B, 1997). Before-after designs aim to support causality between an intervention and a measurable outcome without the restraints or complexity of randomisation. They are usually considered a “second best” option used when a randomised controlled trial is not feasible due to financial, ethical or other practical constraints. The most significant critique of this technique is the failure to control for confounding variables. In the hierarchy of evidence a quasi-experimental design is rated below a randomised control trial and its results are not as persuasive as that of a randomised controlled trial. It is appropriate to perform a before-after study when a randomised controlled trial can not be justified. Ultimately this study design may form the basis for a randomised controlled study as a pilot study or feasibility study. Frequently before-after studies do not contain a true control group so do not control for the effect of natural history or external overwhelming events.

The investigator recognises the particular problems of before-after studies including regression to the mean and temporal effects. The problem of regression to the mean is a particular issue in musculoskeletal medicine where conditions tend to follow a relapsing and remitting pattern over time. Patients tend to enrol for surgery when their condition is particularly severe and so may experience a benefit that they then associate with surgery. Similar effects may be experienced in this study design.

General temporal effects that should be considered here are the tendency of a dysfunctional joint to become stiff, arthritic and more stable. There is not an established link between patellar instability and arthritis, the investigator recognises that temporal effects may be relevant here. One solution could include re-examining the congruity at multiple time points, such as one year, five years and ten years.

Despite the limitations of this study design it is the most appropriate at this point on the research journey. This design was selected due to its limited financial demands, lack of ethical controversy and primarily the fact that no study of this type has been performed before; this study may ultimately form a power calculation for future studies employing a randomised controlled design.

Although an attempt was made to assess the repeatability of the MRI measure of congruence on a given scan we did not assess the repeatability of the measure across different scans. With additional resources an optimal scenario would have been to repeat the scan on the same patient without intervention to assess the reliability of the measurement.

Due to the restrictive cost of the MRI scan we did not validate the measure of congruence. This could be performed by undertaking MRI with a cadaveric knee and then assessing the congruence with contact pressure paper to assess the accuracy of the technique. As it stands we have relied on the work of previous investigators to validate the technique (Heino, 1999).

### **Findings, the literature and implications for clinical practice**

Several authors have previously given attention to activation of the quadriceps mechanism during capture of axial imaging (Martinez et al, 1983; McNally et al, 2000). This study aimed to make its own evaluation of the utility of adding this step to the scanning protocol. The disadvantages of adding this dynamic element is the potential for generation of movement artefact and the addition of a further variable that may increase the variance of the data. The potential benefit however is that, should the data remain useable, the results would be more representative of the physiologic condition that are present during ambulation. The scatter plot of “difference from the mean” for the passive and the active knee demonstrated a floor effect in the quadriceps active knees in full extension that is not so florid in the passive knee group. Activation of the quadriceps pulls the patella superiorly beyond its final point of contact with the trochlea. This is more evident in the pathologic cases than the normal knee cases due to the presence of patella alta in the instability patients.

The large differences in congruence of the patellofemoral joint at different positions of flexion lead us to the conclusion that it is important to standardise the degree of knee flexion when comparing congruence between patients and interventions. This also applies to the patellofemoral indices particularly to Biedert’s ratio of patella height. Care was taken in this study to only make comparisons within a restricted 10-degree range, a more narrow range may be desirable in a larger study.

Despite the small sample size of this study there were significant differences in the contact at all ranges between 0 and 40 degrees when comparing between cases and controls. It is with some interest that we can observe the largest and most significant difference in congruence (1.73cm<sup>2</sup> vs 4.00cm<sup>2</sup>, p<0.005) was at the 11-20 range of knee flexion. This is the range at which patients classically describe dislocations. It is also the position at which the clinician can sublunate the patella during clinical examination. The 11-20 range also enjoyed the greatest improvement in congruence following surgery.

The study is underpowered to determine which of the several interventions is most successful. They are each selected to solve separate underlying pathologic problems so a comparison of them is clinically irrelevant in this context and the results of such a subgroup comparison may be misleading when underpowered.

### **Future work**

This study has demonstrated major differences in congruence of the joint between patients with patellar instability and those with normal knees. Although the study is not powered to break down the outcomes of the various surgical procedures for the various anatomic abnormalities what it does do is indicate to us that it is possible to achieve major restoration of joint congruence.

Although these surgical procedures are designed to stabilise the knee cap they also increase the congruence of the joint. This study also raises the question: Can stabilising the joint and increasing joint contact area be protective against arthritis?

This study aimed to reproduce the conditions of walking by activating the quadriceps. In the next chapter we will discuss a more dynamic evaluation- albeit using less precise methodology to evaluate the effects of patellar instability on gait.

## Chapter 3: Gait and patellar instability

The knee relies on both dynamic and static factors for stability of the patellofemoral articulation and the articulating surface of the patella changes depending on the degree of knee flexion and the patella's position on the distal femur (Goodfellow et al, 1976; Levangie and Norkin, 2005). In the first chapter, we found that the patellofemoral joint was frequently unstable before it degenerated into an arthritic joint. In the second chapter, we found that the area available for force transmission varies greatly by knee position. In cases of patellar instability, the area available for force transmission was less than in the normal knee.

The methodology described in the preceding chapter attempts to reproduce the conditions of locomotion by activating the quadriceps. The quadriceps, however, are but one part of the orchestra of muscular activity required for ambulation. This chapter attempts to capture some of the differences which may be present during walking. In this, chapter we will evaluate what effect patellar instability may have on knee kinematics.

Most forms of medical imaging require a stationary target to attain any image definition. CT and MRI scanning are very prone to movement artefact and have not been successfully used to record images during ambulation. In the preceding study the use of MRI was only possible as the femur was held still whilst the patella rose within it. Inverse dynamics analysis of gait combines kinematic, morphometric and force data in a linked-segment model and is used to evaluate limb joint angular excursions, net joint moments and net joint powers.

I considered adding electromyography (EMG) as an outcome, this would have had the advantage of directly assessing muscle activity rather than inferring this as is necessary in inverse dynamics. I decided not to use the technique for two reasons. The technique is potential uncomfortable for the subject and this would likely result in few attendances for post-operative evaluation of the subjects. The gait analysis centre is situated some distance from the city and there were already challenges with attendance. The second reason was that the gait analysis centre is not set up for sterile technique in humans. Overall I felt that adding this secondary outcome measure could be a challenge to consistently achieving attendance for my primary outcome measure.

### Gait anomalies associated with knee pathology

With the exception of one case report, relating to iatrogenic medial instability, there are no studies of gait relating to patella instability (Sanchis-Alfonso et al, 2007). The few studies which relate to PFJ pain are considered below.

Gait analysis has been used in small numbers of subjects to examine the effect of patellofemoral pain syndrome (PFPS) (Nadeau, 1997; Dillon et al, 1983; Paoloni et al, 2010), knee osteoarthritis (Pohl et al, 2013), total knee arthroplasty (Smith et al, 2006; Li et al, 2013) and surgical changes to the knee joint's lateral retinaculum (Kramers-de Quervain et al, 1997; Sanchis-Alfonso et al, 2007) but to date the significance of patellofemoral instability on gait is unknown. Gait studies on patients with PFPS have identified deficits in gait patterns (Nadeau, 1997; Dillon et al, 1983). Dillon et al found a decrease in knee flexion angles at the beginning of the stance phase for patients with chondromalacia patellae.

Modifications in temporo-spatial parameters of gait have been observed, such as decreased knee joint angular displacement, swing phase angular velocity and cadence (Nadeau, 1997; Paoloni et al, 2010) leading to the conclusion that the patients avoided pain at the PFJ during walking by reducing knee flexion, which then reduced the articular forces at the PFJ. Joint moments in particular can be affected by weakness (Winter, 1980), pain (Murray et al, 1985; Stauffer et al, 1977) and instability (Berchuck et al, 1990). Winter found that there was a knee net flexor moment in late stance in patients after total knee replacement due to the underuse of their knee extensors.

Chesworth et al (1989) found there were no modifications to the gait pattern in PFPS patients following reported improvement in their other symptoms. No authors have sought to identify gait pathology in patellar instability patients and none have evaluated the effect of stabilisation surgery on gait. It is a recurrent theme in the limited patellofemoral gait literature that reduced angular displacement of the knee is the gait feature best correlated with disease of the patellofemoral joint.

The patellofemoral joint reaction forces cannot be easily measured non-invasively, but the overall sagittal knee moment can indicate the pattern of flexor and extensor forces transmitted across the joint. There are significant gaps in the understanding of gait deficits in patients with patellofemoral instability.

### **Quadriceps avoidance gait**

During ambulation, the body weight can be supported by static alignment of the skeleton with gravity or by resisting actively with joint reaction forces resisting collapse of flexed joints. Where pathology affects the quadriceps, and in several other conditions of the knee a characteristic gait develops to minimise the dynamic forces generated in the knee. You will likely have observed this gait pitch-side as you see an injured player make their way off. This gait pattern still relies on the acceptance of weight by the lower limb but, instead of



depending on muscular activity of the quadriceps the weight is supported by more closely aligning the tibia and femur so that less of an angular moment is generated. In its most severe forms (for example after femoral nerve injury) the subject can be seen to compensate with the trunk and lower leg. During weight acceptance, the trunk is flexed and the ankle is forcibly plantar flexed to push the knee into hyperextension. The knee can be further held in extension by the iliotibial band. Where pathology is very severe, or the iliotibial band is also inactive, the subject can be seen to push on their thigh with the palm to maintain extension.

This pain avoidance strategy is known as a quadriceps avoidance gait; it reduces the forces in the patellofemoral joint during walking and may be identified by a reduction in knee extensor moment in early stance during weight acceptance. This occurs again in late stance when the eccentric contraction of the quadriceps would usually control the flexion of the knee and collapse of the leg into swing phase.

In milder cases the pathology can be detected by inverse dynamics. A reduction of total limb support moment indicates a reduction in weight-bearing forces. The patella is the sesamoid bone of the quadriceps and so it can be anticipated that its pathology be detectable by abnormalities of quadriceps function.

## Hypotheses

- Patellar instability influences the sagittal plane extensor joint moment of the knee and the total support moment of the affected limb.
- These differences resolve with patella stabilisation surgery.

It was hypothesized that patients were likely to modify their gait pattern to reduce loading through the patellofemoral joint. The purpose of this study was to compare pre-operative patients with patellofemoral instability against normal control subjects using inverse dynamics analysis of gait. We further hypothesised that following surgery and rehabilitation the observed effects of the patellar instability might be reversed.

## Methods

### Research participants

Thirteen patients with patellar instability (6 male, 7 female, mean age 26) were recruited from the clinical caseload awaiting patella stabilisation surgery at Southmead Hospital, North Bristol NHS Trust. Of the 13 patients, eight reported their right limb to be more affected, or had right unilateral symptoms. Five reported their left limb to be more affected, or had left sided unilateral symptoms. Eight control subjects (5 male, 3 female, mean age 25) with

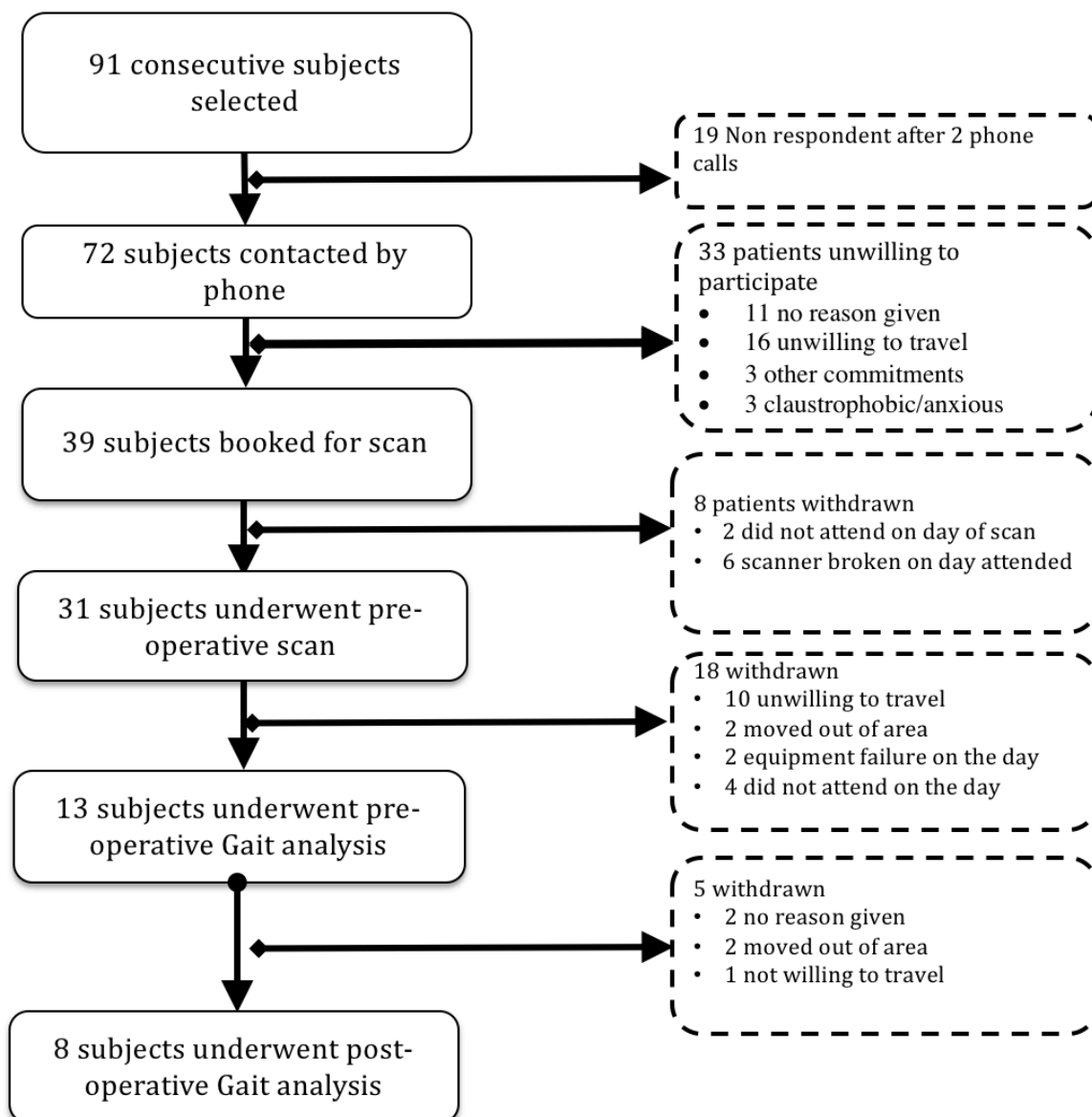
no patellar instability or known gait deficits were recruited for comparison. One of these controls was a research assistant (DS). The readings for this control were repeated every time to equipment was set up in order to ensure consistency of the calibration. Only the first reading is included in the mean data of “all controls”.

### **Inclusion and exclusion criteria**

The study targeted patients with severe and symptomatic instability, severe enough to be listed for surgery. Patients were identified from the list of patients awaiting surgery for patella stabilisation. Inclusion required a history of at least two patient reported episodes of patellar instability with ongoing experience of discomfort or distrust in knee. The same inclusion and exclusion criteria as described for the patella congruence study were used for this study. Patients were excluded if they were unable to provide valid consent, unwilling to participate, aged less than 17 years, suffered degenerative knee joint disease (any radiographic evidence of osteoarthritis), were pregnant or if they were unreachable by phone.

### **Recruitment**

Patients being offered enrolment for the congruence study were also offered involvement in the gait analysis study. In addition to the exclusions from the congruence study a further 18 patients were excluded from this study. The gait analysis laboratory is located a 30-minute drive out of the city and in five cases the exclusions were incurred due to the increased inconvenience of travel. Two occurred due to failure of equipment set up on the first day of post-operative gait analysis, two patients had moved out of area and one did not attend and gave no explanation. A total of 78 patients who were approached were not included, the inclusion rate was 14%. The reason for exclusion are shown in table 21. Of those the initial 13 patients eight returned one year after surgery for post-operative gait analysis. Four of those who returned were female and 4 were male (mean age 34 range 17-42). Between the first and second session of gait analysis the subjects had undergone surgery and subsequent physiotherapy rehabilitation. Those operations included one trochleoplasty, two MPFL reconstructions and five tibial tuberosity transfers.



**Table 22. Inclusions and exclusions flow chart.**

### Data collection

An infrared marker based three-dimensional motion capture system (Qualysis, Gothenburg, Sweden) was used to track gait and gait dysfunction. Four cameras were set up in a staggered array adjacent to the force plate. Six reflective infrared markers were placed on each leg. These were positioned on the fifth metatarsophalangeal joint, distal fibula, centre of rotation of the knee and hip joints and over the iliac crest. A Kistler (Kistler Instrumente AG, Eulachstrasse 22, PO Box 8408, Winterthur, Switzerland) piezoelectric floor based force plate and proprietary software was synchronised with the Qualysis infrared camera system (Qualisys AB, Packhusgatan 6, 411 13 Gothenburg, Sweden).

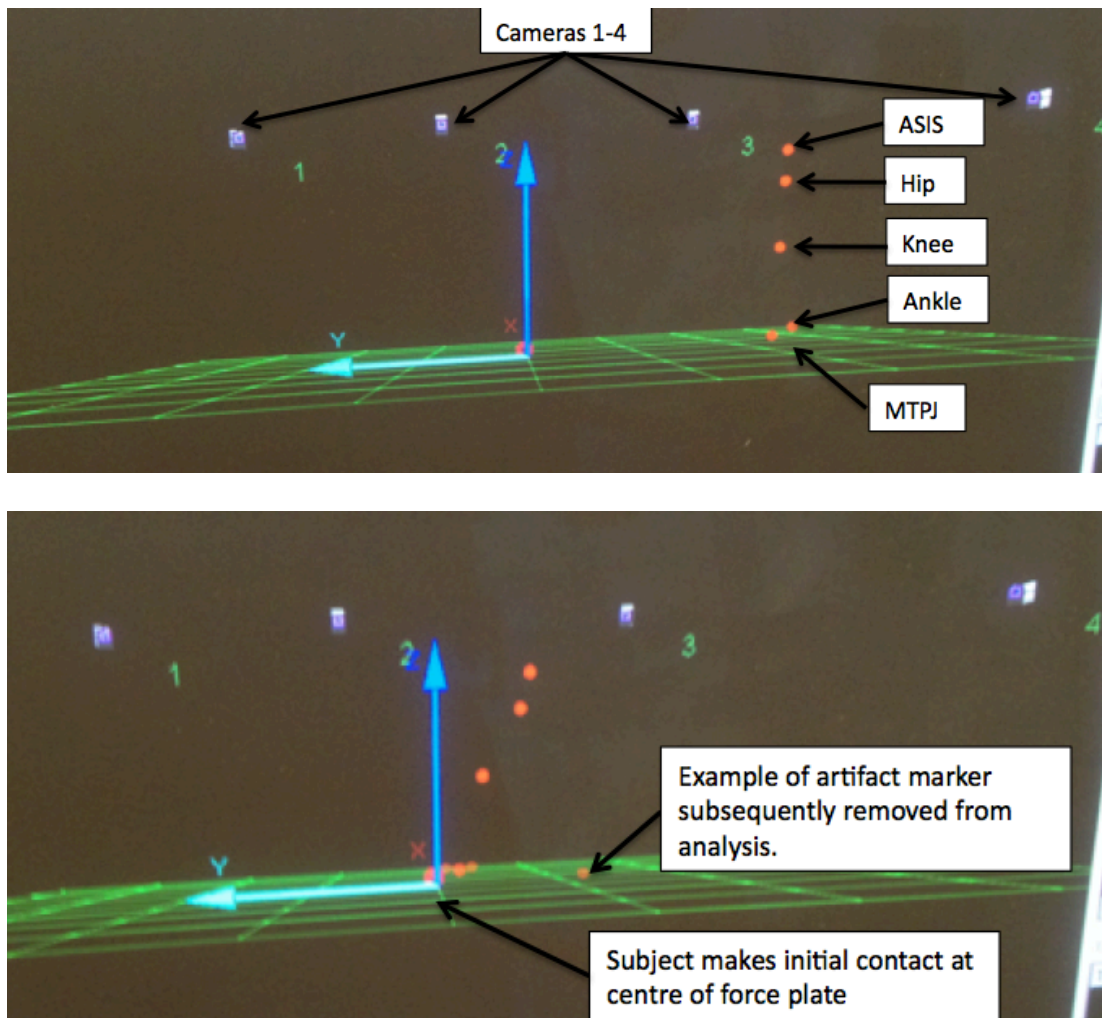


Figure 56. Example of appearance of synchronised output of force and kinetic data. Segments have been labelled for illustrative purposes.

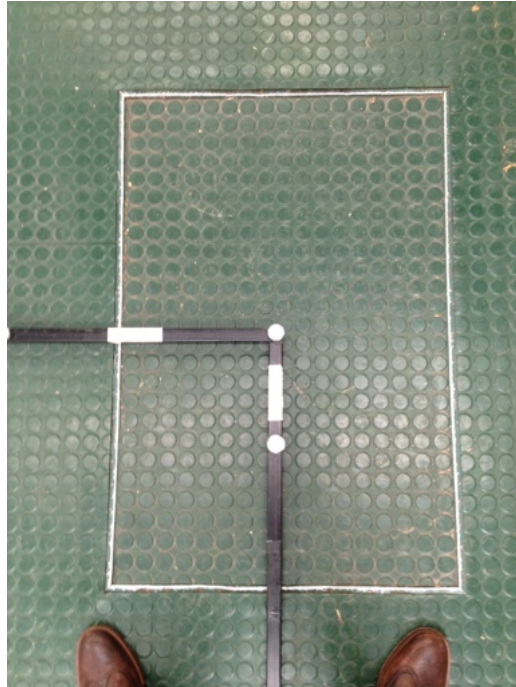
#### Procedures and protocols

Because the subjects visited the facility on two separate occasions (more than a year apart) the study protocol aimed to ensure that the data collection was calibrated by repeating the analysis with the same control on each occasion. For this reason, the research assistant acted as an additional control, the calibration of the data collection tools being checked against the research assistant's gait data. The same control repeated their data collection each time the equipment was set up to ensure consistency between setups. This data also constituted the repeated measures analysis. The threshold for an acceptable reading was the presence of an extensor moment during weight-bearing. This was found in all cases for the controls, across subjects and within the repeated measure subject.

#### Gait analysis

The force platform location was calibrated in the three-dimensional kinematic volume of space and recorded the ground reaction forces (GRFs) in the vertical ( $F_z$ ), antero-posterior

(Fy) and medio-lateral (Fx) directions in synchrony with the 3D kinematic data collection. The kinematic X, Y and Z calibration axes were aligned with the force platform X, Y and Z axes. Figure 57 illustrates the use of the calibration device to centre the infrared array over the force plate. Kinematic and force data were collected at 200Hz for three seconds per trial.



**Figure 57. Calibration device laid over force plate.**

Prior to arrival of the subjects on each day of the analysis we repeated the gait analysis on the same normal control subject (my research assistant) to ensure consistent data collection. Subjects wore tight leggings or shorts for gait analysis and walked in their socks without shoes. To identify limb segmental endpoints spherical retroreflective markers (18mm diameter) were affixed with adhesive tape to the skin or leggings overlying the fifth metatarsophalangeal joint, ankle, centre of rotation of the knee, hip joint and iliac crest on both left and right lower limbs. The metatarsophalangeal joint marker was placed on the distal extremity of the fifth metatarsal bone, the ankle marker on the lateral malleolus, the knee marker on the lateral epicondyle of the femur, and the hip marker on the greater trochanter. An additional marker was placed on the iliac crest to identify the pelvis as a segment for calculation of the hip joint angle. Marker placement was based on palpation of the underlying bony landmarks and visual confirmation of placement symmetry between sides.



Figure 58. Arrangement of reflective markers. These correspond to the points in figure 54.

Prior to data collection, subjects were instructed to undertake a series of practice walks at their own, self-selected natural pace along a 10m walkway equipped with a Kistler force platform<sup>a</sup> embedded flush in the floor and a 4-camera Qualisys kinematic system<sup>b</sup> set-up in a semicircle and focused on the area around the force platform.

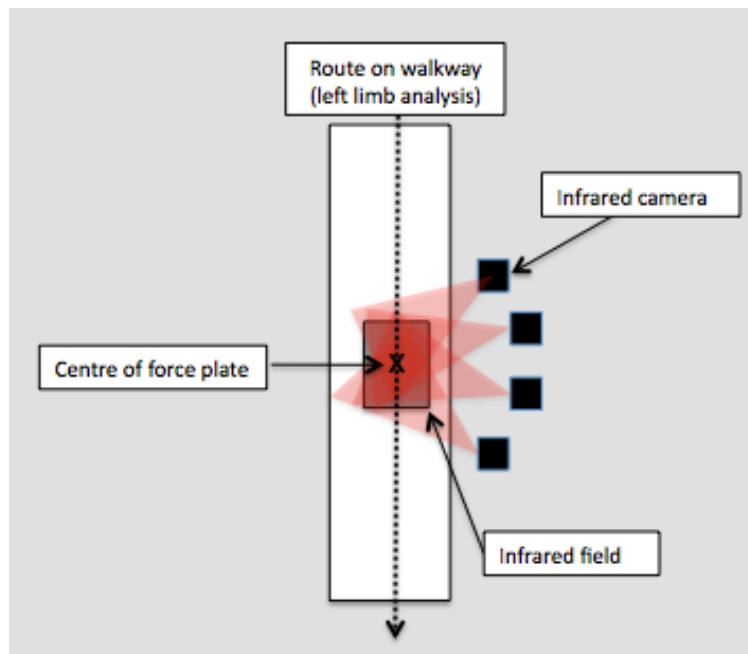
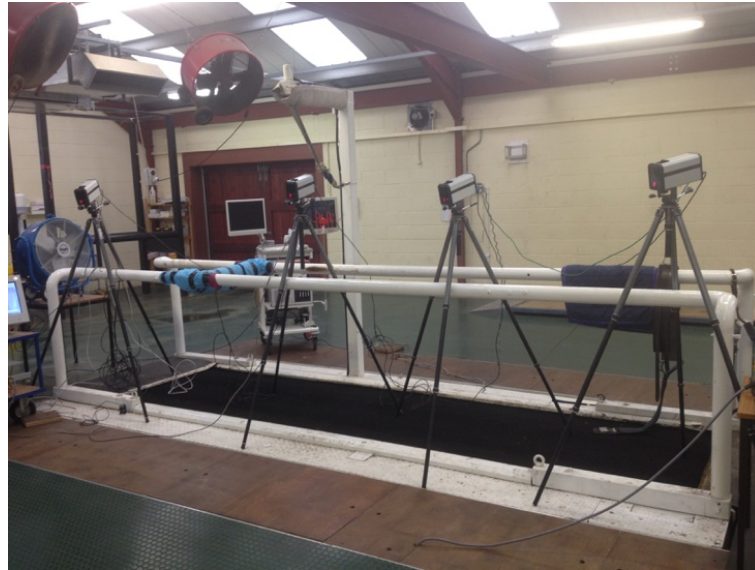


Figure 59. Arrangement of infrared camera array and force plate. Correspond with image 60.





**Figure 60. Infrared camera array. Force plate (out of shot) is to left of photographer.**

The subjects walked in both directions along the walkway and six trials of kinematic and force platform data from each limb were collected for each subject. Trials were only accepted when the limb closest to the cameras struck the force platform near the centre during a normal stride. At times the stride resulted in the foot contacting the force plate too far forwards or backwards. The starting point for the subjects' walk was gradually adjusted until they consistently struck the centre of the platform. After data collection and before removal of the markers, the subjects were weighed and distances between markers on the limb were recorded as a measure of segment lengths. Segment masses were calculated as a percentage of total body mass (Dempster, 1955).

### **Data analysis**

#### **Gait Data Analysis**

Qualisys Track Manager<sup>b</sup> was used to identify and track marker motions from the raw kinematic data. Markers were manually assigned the labels of Anterior superior iliac spine, hip, knee, ankle and metatarsal phalangeal joints. Although efforts were made to ensure that the subjects wore clothing free of reflective material and that the background be kept free of reflective material, at times redundant artefact markers made an appearance in the background. When this was immediately identified these reflective areas were covered with tape and the data capture repeated. Any residual artefact markers that may appear as a result of the camera detecting other reflective material on clothing or in the background were later removed manually.

Data was combined with each subject's limb morphometric data and the force data in a custom program to calculate ankle, knee and hip net joint moments in the sagittal (YZ) plane using inverse dynamics (Winter 2005). The sagittal plane GRF vector, was calculated from the  $F_y$  and  $F_z$  forces and the appearance and disappearance of this force vector identified the beginning and end of the stance phase.

Net joint moments were calculated to be negative on the posterior or plantar side of the limb and were normalised to each subject's body mass. The six normalised trials per limb per subject were averaged within subjects and then further ensemble-averaged across subjects

#### Total Support Moment (TSM)

TSM was calculated as the sum of all the individual net joint moments after reversing the sign of the moment at the knee so it was negative on the anterior side of the knee joint before including it in the sum with the other joints. In this way, all the moments contributing to anatomical extension of the joints were summed as the TSM. For each patient, right and left TSMs were plotted and used to identify which limb was more and less affected. TSM curves were then compiled for the more affected and less affected limb in each of these patient subgroups for comparison against the control curves and against each other.



## Results

Two subgroups were evident in the overall group of clinical patients according to the profiles and amplitudes of the normalised knee moment curves: one with similar left-right knee moment profiles and at least a small knee extensor moment during the weight acceptance period in early stance (group P1, n=5), and one with no extensor moment during weight acceptance in early stance (group P2, n=8). The hip, knee and ankle moments from both the more affected and less affected sides were then averaged per patient group.

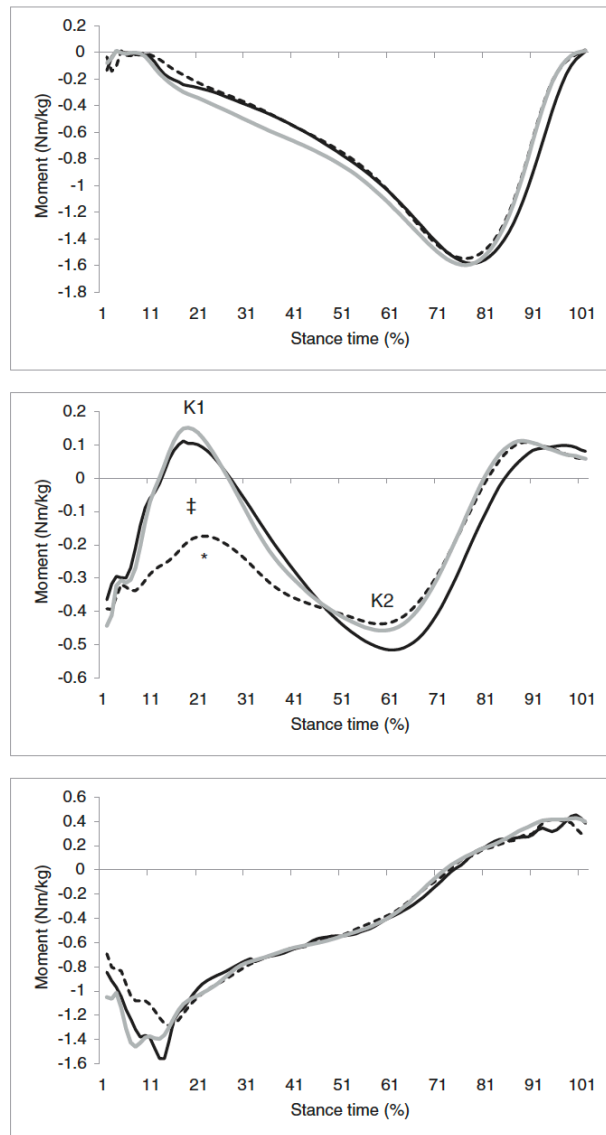
	All patients mean (SD)	P1 mean (SD)	P2 mean (SD)	Normal controls
Insall-Salvati ratio	1.39 (.14)	1.19(0.13)	1.54 (0.16)	-
TTTG offset.	1.9 (3.1)	9.6 (2.1)	13.9 (4.7)	-
Number with trochlea dysplasia	5/13	1/5	4/8	-
n previous dislocations	3.4	1.4	4.2	0
Beighton score	3.2 (1.9)	1.2 (1.79)	6.0 (3.9)	-

**Table 23. Anatomic features of subjects in P1 and P2.**

At intake, five of the clinical patients were categorised into group P1 on the basis of their knee joint moment profiles. These five patients all demonstrated at least a small extensor moment in early stance, during weight acceptance on their limbs. Analysis of each patient's TSMs indicated that the right limb was the more affected limb in two of these five patients and the left limb in the other three. The other eight clinical patients demonstrated no knee extensor moment during weight acceptance and so were placed in group P2. In this group, the right limb was the more affected limb in six, and the left limb more affected in the other two on the basis of their TSMs. The table above illustrates the various anatomic features of the patients in groups P1 and P2, no imaging data was available for the normal controls.

The control group include people with no history of knee trauma, pain or surgery. They do not undergo any intervention as part of this study and represent the normal baseline. The collected once for each control with the exception of the research assistant control who's data was collected every time the equipment was set up. The left and right lower limbs TSMs

generated in the normal control subjects were similar in amplitude and shape. There were no significant differences between limbs in peak values of early or late stance. Therefore, the normal control group's left and right TSMs were combined and averaged to act as a normal data reference.



**Figure 61. Ankle (top) knee (centre), hip (bottom). Net joint moments in stance. Control, P1 and P2 groups. Solid grey line is Control, solid black line is P1 and dashed black line is P2. The curves represent the combined and averaged data from both right and left limbs in each group. K1 and K2 are the two peaks in the knee moment curve, corresponding to the normal knee extensor moment in early stance and the knee flexor moment in midstance, and the values reported in Table 24 are for those two peaks per subject. \*Peak knee moment for group P1 is significantly different from group P2. ‡Peak knee moment for group P2 is significantly different from Control group. K1 represents the (quadriceps dominant) extensor burst on initial loading of the limb, K2 represents the maximum knee moment in which the flexors are dominant.**

	K1			K2		
Control	0.15	0.15	-0.18 to 0.36	-0.46	0.10	-0.22 to -0.60
P1 More aff.	0.08	0.09	-0.03 to 0.20	-0.57	0.10	-0.47 to -0.69
P1 Less aff.	0.15	0.13	0.02 to 0.31	-0.51	0.20	-0.16 to -0.67
P2 More aff.	-0.26	0.12	-0.04 to -0.41	-0.51	0.24	-0.19 to -0.89
P2 Less aff.	-0.04	0.16	-0.34 to 0.18	-0.40	0.17	-0.19 to -0.70

Table 24. Knee moment at K1 and K2 in groups P1 and P2.

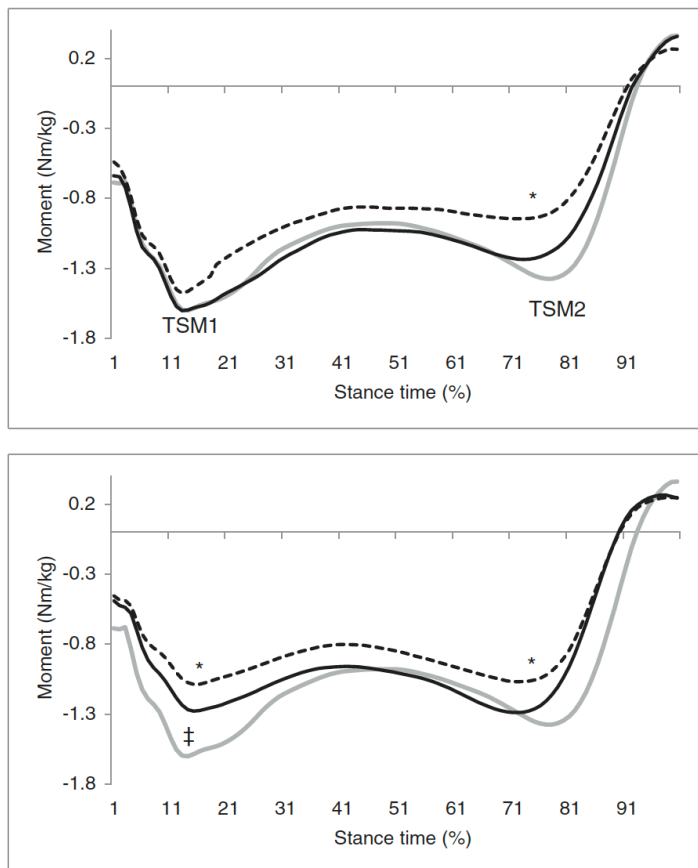


Figure 62. Total support moment. for P1 (top) and P2 (bottom). Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs. Grey line is Control group TSM. TSM1 and TSM2 are the two peaks in the TSM curves, corresponding to early stance and late stance, and the values reported in Table 25 are for those two peaks per subject. \*More affected limb TSM is significantly different ( $P < 0.05$ ) from the corresponding Control group peak. Less affected limb TSM is significantly different ( $P < 0.05$ ) from the corresponding Control group peak.

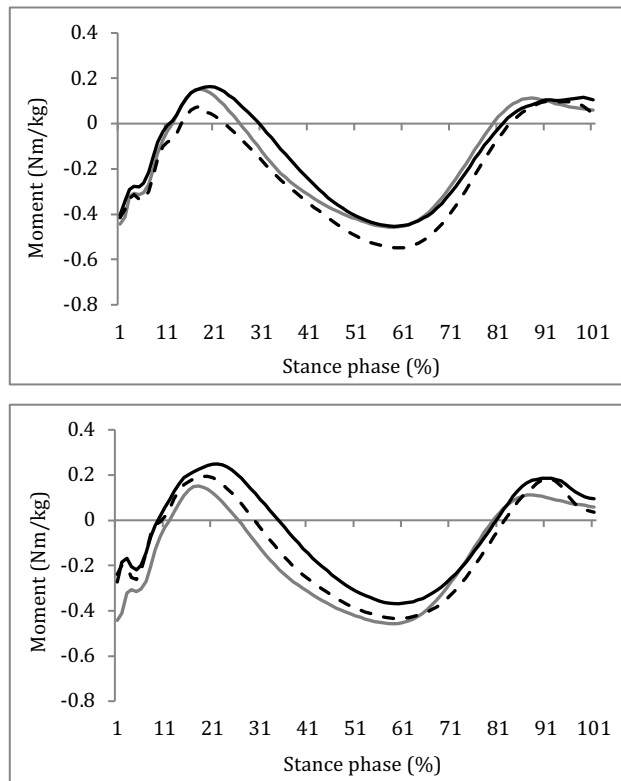
TSM1 and TSM2 are the two peaks in the TSM curves, corresponding to early stance and late stance and the values reported in Table 2 are for those two peaks per subject. More affected limb TSM(\*) is significantly different ( $P < 0.05$ ) from the corresponding Control group peak. Less affected limb(‡) TSM is significantly different ( $P < 0.05$ ) from the corresponding Control group peak.

Group	TSM1			TSM2		
	Mean	(SD)	Range	Mean	(SD)	Range
Control	-1.59	0.21	-1.30 to -1.88	-1.40	0.24	-1.00 to -1.85
P1 More aff.	-1.46	0.37	-1.02 to -1.93	-0.90	0.20	-0.72 to -1.15
P1 Less aff.	-1.57	0.35	-1.18 to -2.12	-1.22	0.29	-0.98 to -1.70
P2 More aff.	-1.18	0.25	-0.82 to -1.54	-1.18	0.30	-0.50 to -1.41
P2 Less aff.	-1.32	0.21	-1.08 to -1.58	-1.26	0.25	-0.92 to -1.63

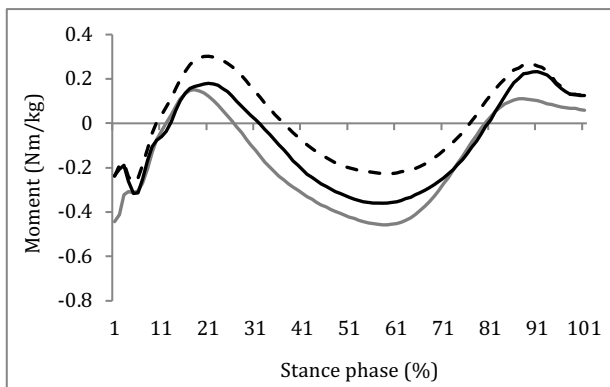
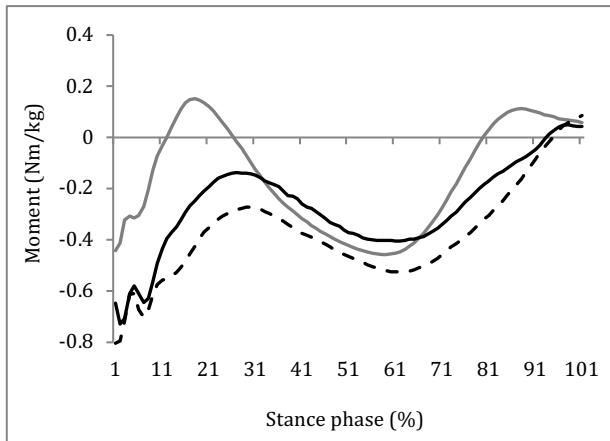
**Table 25. Total support moment of patients in P1&2 at points TSM1 & TSM2.**

**Post-operative results:**

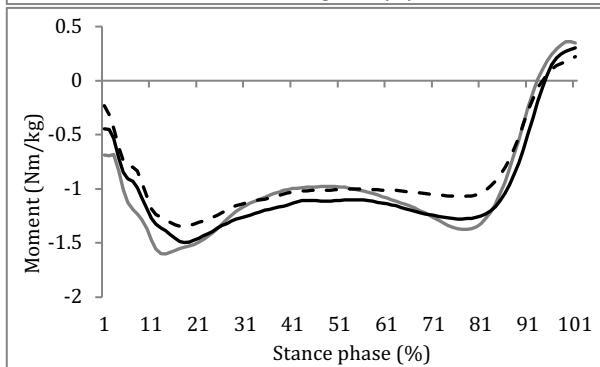
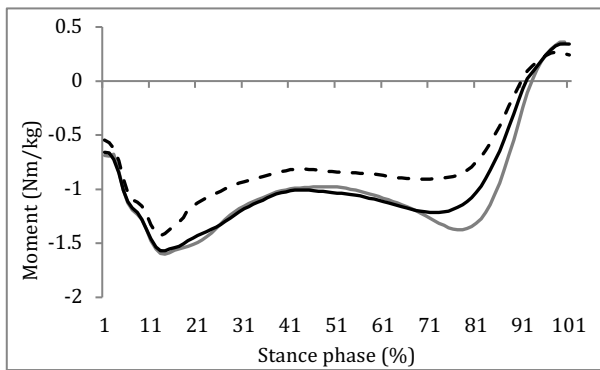
The following data constitutes the data from the patients who returned for post-operative gait analysis. Figure 63 indicates that pre-treatment TSM for the more affected limb of group P1 was consistently smaller through the stance phase than the control curve and that of the less affected side. There was minor improvement following surgery. The TSM profile of the less affected limb of this group was not noticeably different from the Control curve at either measurement point. The pre-treatment TSMs of both limbs in group P2 were smaller than the Control values in early stance but only the more affected limb demonstrated values that were slightly smaller than normal control values in late stance. In this group, the main change following treatment was during the weight acceptance phase in early stance where the oscillation observed during loading was reduced and the TSM was increased.



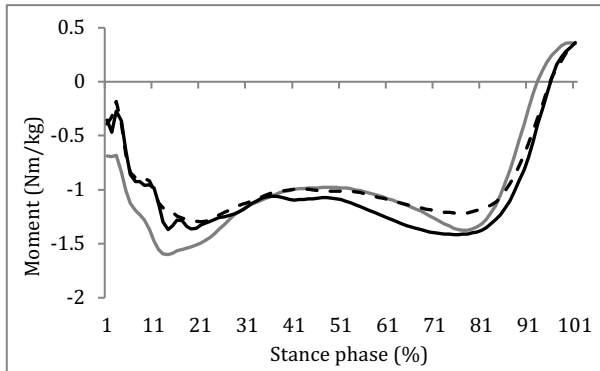
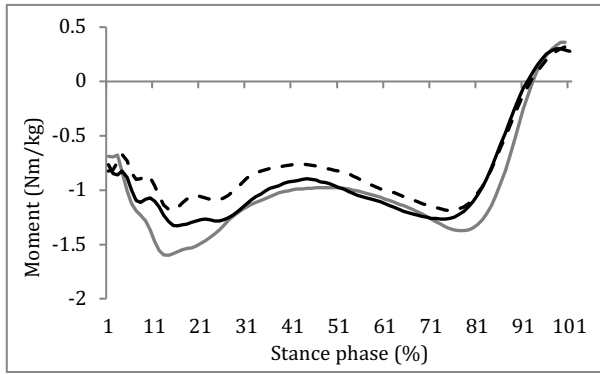
**Figure 63. P1 Pre-operative (top) and post-operative (bottom) knee moments.** Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs. Grey line is normal group.



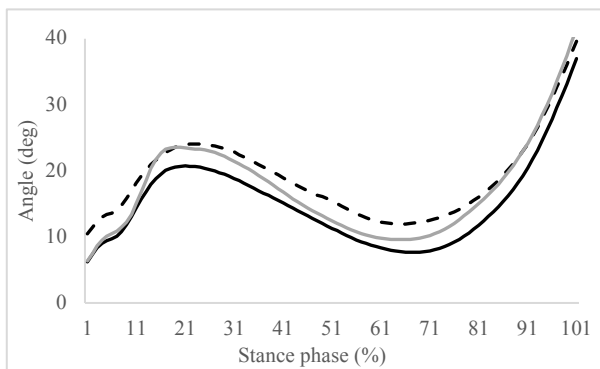
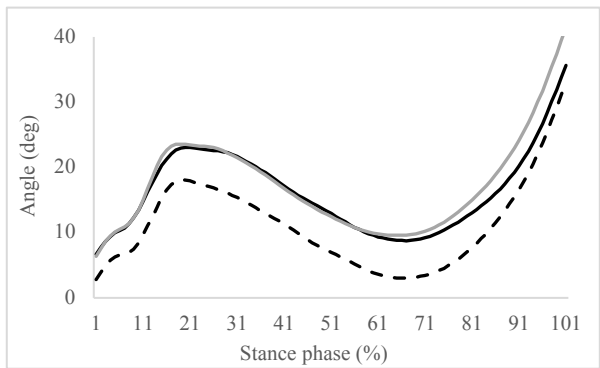
**Figure 64. P2 Pre-operative (top) and post-operative (bottom) knee moments.** Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs. Grey line is normal group



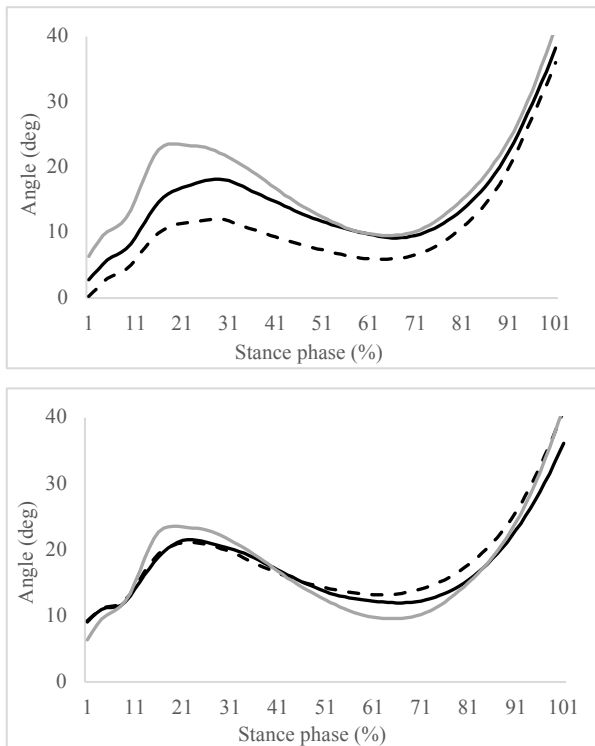
**Figure 65. P1. Pre-operative and post-operative TSM.** Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs, grey line is normal group



**Figure 66. P2. Pre-operative and post-operative TSM.** Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs. Grey line is normal group.



**Figure 67. P1. Pre-operative and post-operative knee angles.** Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs. Grey line is normal group.



**Figure 68. P2. Pre-operative and post-operative knee angles.** Solid black line is the less affected limb, and dashed black line is the more affected limb according to each patient's individual TSMs. Grey line is normal group

The knee joint moments for the two patient groups are illustrated in the figure above, overlaid on the control data. The moments generated across the knees of the more affected and less affected limbs are shown in comparison to the combined right and left knee moments of the control subjects. For group P1, who demonstrated near-normal knee joint moments pre-treatment, the post-treatment curves indicate an increase in the mean knee extensor moment during early stance on both the more and less affected sides. Post-treatment, the peak knee extensor moment on both sides was larger than the mean control values. Likewise, at the end of stance, the extensor moment exerted by the quadriceps as the knee extensors controlled the knee's collapse into the swing phase was larger than the control value on both sides. For group P2, who did not demonstrate a knee extensor moment in early stance pre-treatment, there was a large improvement with mean peak values for both the more and less affected limbs exceeding the control values in both early and late stance.

## Discussion

Gait analysis can be performed using several different techniques. Kinematic analysis performed by three-dimensional assessment of limb segment position linked to force plate data

represents the most accurate available technique. The research tools are extensively validated; however even the most advanced gait analysis equipment is subject to variation depending on location and observer. To validate the experimental setup in this study an acceptable normal control group was analysed. The gait analysis was performed on different days for the convenience of the subjects. Pre-operative and post-operative analysis and were performed one year apart. The use of the same control subject to verify calibration of the equipment permitted consistency across each visit.

### **Strengths**

The sample size for the gait study is smaller than that of the congruence study. No power calculation was used as there is very little relevant literature in this area. Despite its small size the study remains the largest study of its kind and is of equivalent size to other studies of similar areas. Gait analysis is a resource intense process, requiring not only the time of the participant and researcher to collect the data but also significant time spent in labelling and interpreting the results.

It is possible to argue that selecting out severe cases (P2) from the entire studied population (P1 + P2) is a method of artificially inflating the significance of the findings. However given that this is early and exploratory work I would argue that identifying the patient subgroups is a more relevant activity than describing the outcomes of what appears to be a heterogenous. I would argue that the finding of two spectral groups within this cohort is out most significant finding.

### **Weaknesses**

Reasonable criticisms of the study design here are the same as for the congruence study. The before-after nature of the study and lack of a true control group makes establishing a causal relationship impossible. The objective of our control group was to established normal range. There are many different gait parameters that have been described. Gait can be described in kinetic or kinematic terms; it can be described in the sagittal and coronal planes. This study has several limitations stemming from its design, so clinical application of its results are restricted. One criticism of the study may be that three different surgeries were used to correct the instability. Although this is the case, the surgeries in all cases aimed to create normal anatomy by correcting the underlying abnormality whether that was patella alta, trochlear dysplasia, or MPFL rupture. Although three techniques were used, the intervention is a move from abnormal to normal anatomy, and the results reflect this change. Although the study is the largest of its



type, it remains small due to the significant resources required to assess each patient. The major limitation of the study is in the before-after design; it remains uncertain if the changes came about due to the surgery or the subsequent physiotherapy or simply the passage of time. A randomised trial of physiotherapy versus surgery and physiotherapy would effectively tackle this question. The “Patellar instability, Physiotherapy or Surgery” is just such a trial and is currently recruiting (Metcalf, 2016).

### **Findings and the literature**

The most dramatic change observed post-operatively was the appearance of an early stance net extensor moment at both knees in patient group P2. Whereas pre-operatively this group demonstrated the classic “quadriceps avoidance” mechanism to reduce patellofemoral forces in stance, post-operatively they could generate an extensor moment to support the knee in both early and late stance. In early stance, the knee extensors control the flexion of the knee, and produce its subsequent extension as the knee works like a shock absorber after foot contact, by generating a net extensor moment that is first eccentric, and then concentric. Through mid-stance, the knee flexors are the net active muscle group, as the hamstrings are active to produce hip extension. As this muscle group also crosses the knee, they exert a flexor effect by combining with the ankle plantar flexors which are controlling the dorsiflexion of the ankle during early and mid-stance. In late stance, the knee extensors control the collapse of the knee into flexion at the transition between the stance and swing phases. The improvement in knee extensor function had an impact on the TSM in both groups, although this measure is confounded by any change in function of the hip and ankle muscle groups and by changes in walking velocity. Overall, TSM is a reflection of the function of the total limb as it supports the incumbent body during stance and the extensor and flexor moments per joint are additive. Increasing the extensor moment at the knee might simply add to the extensor (plantarflexor) effects at the hip and ankle, for an overall increase in TSM, or it might well reduce the requirement for those other joints to contribute to support. The results shown here indicate that TSM on the more-affected side mainly changed through mid-stance in patient group P1 and this is matched against a reduction in knee flexor moment in mid-stance. Patient group P2 demonstrated the same mid-stance effect, and there was an additional small improvement in the period immediately after foot contact.

We must bear in mind when evaluating moment curves for a particular joint that they represent the “net” effect of the flexor or the extensor muscle groups at a joint. A net extensor

moment indicates that the extensors are the dominant muscle group at an instant in the gait cycle. This does not describe the effect on joint force by the also contracting antagonistic muscle group on the other side of the joint. If both muscle groups increase or decrease their activity the moment can remain unchanged, this balanced contraction is known as co-contraction. There are neuromuscular gait pathologies, for example cerebral palsy, which are characterised by co-contraction. Co-contraction can be useful as it will stabilise a joint. In this study, the more affected knee of group P1, and both knees of group P2 were more extended in early stance. Pre-operatively the knees in group P1 demonstrated approximately the same (between left and right) range of motion through stance, these findings also matched the control group. However, in group P2 both knees were relatively less flexed and demonstrated reduced range of motion in early stance.

Combine the knee flexor moments in early stance with this observation of smaller amplitude of flexion and there is an argument for co-contraction around the knee in early stance in this group to brace it against movement, as is seen in subjects with painful joints. Post-operatively, both groups normalised their knee angular motion, suggesting rehabilitation of the gait cycle. It is also interesting that the anatomic features in group P2 appear to be more abnormal than those in P1.

## **Conclusions**

During normal gait, eccentrically controlled hip, knee and ankle flexion permits shock absorption across those joints after foot contact with the ground. The process is dynamic and fear, pain or quadriceps weakness/avoidance will disrupt the normal gait pattern. The compensatory pattern is a stiffer gait with the knee more extended and the hamstrings dominating as the net active muscle group in early stance. The extended knee position facilitates this by placing the knee's centre of rotation behind the sagittal ground reaction force vector. Weight bearing becomes more reliant on the static restraint of the skeleton than on balanced concentric and eccentric muscle activity.

The current study demonstrates that it is possible to measure rehabilitation of the patellofemoral function after surgery objectively, using gait pattern as a functional outcome measure. Gait analysis enables more precise reporting for the benefits of surgery. In this population, the objective of surgery is rehabilitation of muscular control to a level where return to sports is possible. Reporting of results should match this objective rather than relying solely on crude or subjective measures such as further dislocation and pain scales.

We found that amongst some of these small number of patients that patellar instability influences the sagittal plane extensor joint moment of the knee and the total support moment of the affected limb. These differences do appear to improve after patella stabilisation surgery and a year of physiotherapy rehabilitation.

## Summary of findings and final reflection

In this series of studies we build the link between patellar instability and arthritis. Patients with patellofemoral instability experience dislocations that may cause cartilage damage, they also have abnormal joint anatomy, biomechanics and gait. These biomechanical abnormalities are due to abnormalities of anatomy joint and may lead to abnormal loading of the joint and cartilage damage. It is not known which of these potent pathological pathways between instability and arthritis is most significant.

The first chapter reviewed the literature pertaining to the aetiology of patellofemoral arthritis. This common condition is at times asymptomatic. Several previous studies have explored a link between patellofemoral malalignment and cartilage changes. The conclusions drawn in those studies are problematic as they rely on the assumption that cartilage anomaly will translate into arthritis and that arthritis will translate into symptomatic arthritis. An unmatched case-controlled study was performed using a multivariate analysis to weigh several of the potential confounders. The study accurately measured one anatomic abnormality of patellofemoral anatomy. We found that patella alta was associated with the development of symptomatic arthritis in the patellofemoral joint. This anatomic abnormality is correlated with patella dislocation; therefore patellar instability was assessed as a risk factor. The current study found that these patients frequently present with patellar instability in their youth. Patellar instability in youth frequently precedes degenerative disease in later life.

The second chapter evaluated the literature pertaining to clinical measurements made of the patellofemoral joint. A wealth of measurements relating to patellar instability were identified, many repeating the work of previous investigators. A technique for the accurate measurement of joint congruity by summing the findings on the axial scan was identified. This technique was applied in an active joint to evaluate the congruence of the patellofemoral joint during quadriceps activation. The study found that there was reduced congruence throughout flexion in the patellar instability patients. In the smaller number of post-operative cases there was an improvement in congruence of the joint as an unintended positive effect of joint stabilisation. This study did not permit measurement of the forces across the patellofemoral joint. It is an interesting observation that the PFJ becomes more congruent during flexion, these findings reflect the findings of Lucyk's findings that the joint is under greater pressure as the knee flexes. When our congruence graph is viewed alongside Lucyk's force graph we can

appreciate how the joint is designed (in the normal situation) to deal with the forces set upon it.

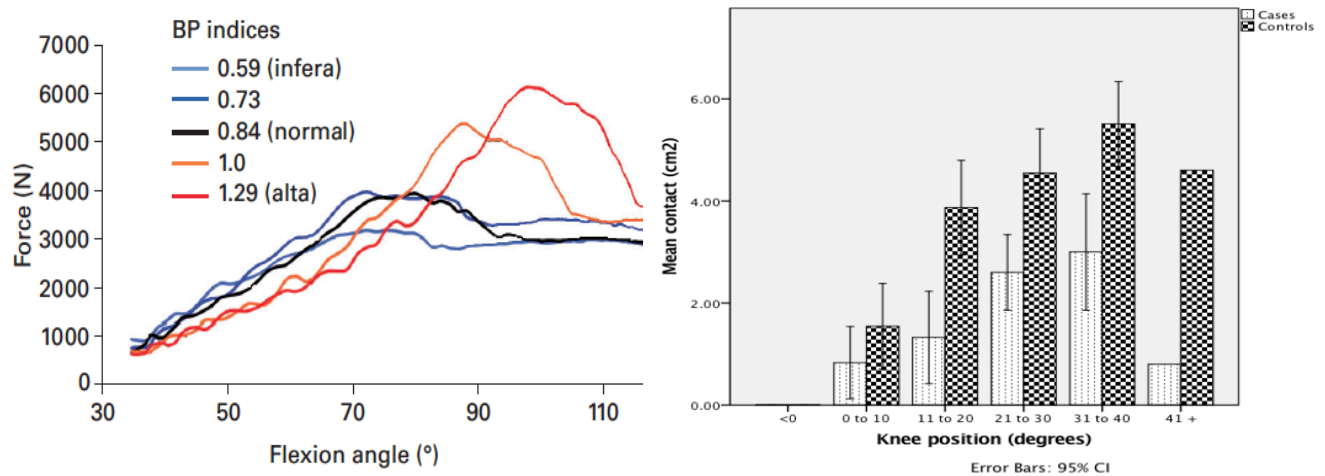


Figure 69 Lucyk's force graph (left) and the congruence graph from the current study (right)

In the third chapter a small number of patients underwent gait analysis before and after surgery. In these patients with patellar instability some had a severe gait abnormality. The characteristic “quadriceps avoidance” gait was identified amongst these patients, the gait returned to normal following patella stabilisation and physiotherapy.

Although the research contains flaws it makes a valuable contribution to the literature. The most significant limitation to consider is the representativeness of the sample. In the first study we did not seek to enrol 475 of 665 potential cases and we did not seek to enrol 1942 of 2387 controls. These unapproached cases and controls were excluded for reasons of convenience, having taken part in other recent follow up or as their surgery was too long ago. I believe them to be representative and am not concerned regarding bias amongst these. A greater opportunity for the role of bias comes in the non-respondents. Although I evaluated the demographic features of this group and found there to be no significant difference (t-test,  $P < 0.05$ ) between the two groups this does not speak to their experience. I have not evaluated the role that a poor outcome of surgery or other experiences might have on responses to questions regarding earlier experiences. Confounders were poorly evaluated in some parts of the study; for example I relied on database information for assessment of BMI in the first study and on the hospital notes for hypermobility information in the second study. Both of these provided poor yield and a potential source of confounder error. In retrospect It would have been preferable to have collected that data in my questionnaire data.

Throughout the studies the theme that the unstable joint is a stressed joint recurs. In the first of the three studies, we observed that abnormal anatomy and stresses are a risk factor for arthritis. In the second study, we see that the unstable joint is an incongruent joint with a reduced area for transmitting forces. In the final study, we observe the mechanisms adopted to reduce the joint reaction forces at the knee in these patients.

There are several anatomic pathologies that appear to overlap in patients with patellar instability and patellofemoral arthritis. These include patella alta, trochlea dysplasia, rotational abnormalities and joint hypermobility. What factor links them remains obscure. It may be that trochlea dysplasia and patella alta are secondary to joint hypermobility and rotational abnormalities represent a separate pathology. Although thought to be familial conditions, very little work has been performed to assess what role genes may play.

#### Future directions

In Bristol, we have the resource of the “Avon Longitudinal Study of Parents and Children” (ALSPAC), a longitudinal study of 14,000 families with up to date data of 4000 patients into their mid 20s. ALSPAC is a resource of phenotypic, environmental and genetic data gathered from different cohort groups over almost 25 years. This data set may prove to be an extremely useful resource for future work as we advance our understanding of the pathology of the patellofemoral joint. The current literature fails to establish a definitive causative relationship as the longitudinal data is limited. As we see these patients coming through to fifties we will be able to evaluate what effect patella instability had on the development of arthritis.

The abundance of patellofemoral indices in the literature is striking, these are used to plan surgery and evaluate outcomes. These indices are often designed to extrapolate what the forces might be passing through the joint without actually measure contact area or force. In this thesis we have concentrated on the use of simple measurements that can actually be used to evaluate the pressures placed upon the joint cartilage in  $\text{cm}^2$ . Although current technology does not permit this the goal of future work should be to describe contact, forces and pressure during ambulation out of the laboratory environment. In the mean time we should focus on describing the joint with natural measurements such as force, area and pressure rather than easily measured but potentially irrelevant or misleading indices.

## Publications arising from this work

Clark, D. A., Simpson, D. L., Eldridge, J. & Colborne, G. R. 2016. Patellar instability and quadriceps avoidance affect walking knee moments. *Knee*, 23, 78-84.

Conchie, H., Clark, D., Metcalfe, A., Eldridge, J. & Whitehouse, M. 2016. Adolescent knee pain and patellar dislocations are associated with patellofemoral osteoarthritis in adulthood: A case control study. *Knee*, 23, 708-11.

Clark, D., Metcalfe, A., Wogan, C., Mandalia, V. & Eldridge, J. 2017. Adolescent patellar instability: current concepts review. *Bone Joint J*, 99-B, 159-170.

## Appendix 1

Correlations											
	Diagnosis	Gender	Laterality	WEIGHT	Age_at_surgery	Patella_height_classification	Isr	AgePain	Unstable	Ageunstable	Dislocation_history
Diagnosis	Pearson Correlation Sig. (2-tailed) N	1									
Gender	Pearson Correlation Sig. (2-tailed) N	.211** 542									
Laterality	Pearson Correlation Sig. (2-tailed) N	-.018 .698 539									
WEIGHT	Pearson Correlation Sig. (2-tailed) N	-.035 .573 255									
Age_at_surgery	Pearson Correlation Sig. (2-tailed) N	-.476** .000 531									
Patella_height_classification	Pearson Correlation Sig. (2-tailed) N	.385** .000 267									
Isr	Pearson Correlation Sig. (2-tailed) N	.509** .000 268									
AgePain	Pearson Correlation Sig. (2-tailed) N	-.616** .000 286									
Unstable	Pearson Correlation Sig. (2-tailed) N	.157** .004 341									
Ageunstable	Pearson Correlation Sig. (2-tailed) N	-.637** .000 202									
Dislocation_history	Pearson Correlation Sig. (2-tailed) N	.287** .000 341									
Diagnosis											
Gender											
Laterality											
WEIGHT											
Age_at_surgery											
Patella_height_classification											
Isr											
AgePain											
Unstable											
Ageunstable											
Dislocation_history											

Table 26. Crosstab correlation of co-variables. Table included for reference. In this table the row diagnosis indicates the dependent co-variable, in this case a diagnosis of PFJ arthritis rather than medial arthritis amongst the patient group.



## References

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