The effect of medial unicompartmental knee replacements on the kinetic and kinematic parameters of the knee: The role of alignment and the effect of articular surface on regulation of medial compartment loading

Joby John

A thesis submitted in partial fulfilment of the requirement of Staffordshire University for the degree of Doctor of Philosophy

May 2013

To

John, Maryrose & Reena,

for letting me have their time,

my mother for her constant prayers.

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Abstract

Medial compartment loading is a significant factor in the progression of medial compartment osteoarthritis and medial unicompartmental replacement arthroplasty is a popular surgical treatment for medial unicompartmental knee osteoarthritis. However, there is no consensus on importance of alignment in medial unicompartmental knee replacement in orthopaedic literature. Static alignment measures like Hip Knee Ankle (HKA) angle and location of mechanical axis (MA) on the tibial plateau are known to affect loading of the knee. In addition, Peak knee adduction moment (PKAM) and angular adduction impulse (Add Imp) measured on instrumented gait analysis are recognised proxies for medial compartment loading especially in the coronal plane. A review of ninety four unicompartmental knee replacements revealed that survivorship at 10 years was 94% and at 15 years was 87%. Significantly better ($p<0.01$) function scores as measured by the 50 point Bristol Knee score was demonstrated in knees with good alignment where the mechanical axis passed through zones 0 or 1.

An investigation into 18 medial unicompartmental knee replacements resulted in a statistically significant improvement in all domains of WOMAC score and the modified knee society score. Medial unicompartmental replacement arthroplasty resulted in a statistically significant improvement in gait velocity ($p<0.01$) and double limb support time ($p <0.001$). Further investigations into the kinetic and kinematic parameters showed excellent reliability. The coronal plane kinetics, peak knee adduction moments (ICC = 0.99), sagittal plane kinematics, flexion (ICC =0.98), sagittal plane plane kinetics, flexion extension moment (ICC =0.87), transverse plane kinematics, rotation (ICC=0.87) and transverse plane kinetics, rotation moment (ICC =0.76) showed excellent reliability as per Fleiss's classification for intra class coefficients. Only coronal plane kinematics, varus valgus (ICC= 0.66) did not fall into the excellent category, but was still considered good.

The coronal plane loading parameters improved significantly following medial unicompartmental replacement ($p<0.05$). The reduction in loading was related to the correction in alignment. The only sagittal plane kinetic parameter that improved significantly following medial unicompartmental replacement was the early stance extension moment (p

=0.05). The transverse plane kinetics, sagittal, coronal and transverse plane kinematics did not show statistically significant differences between the preoperative and postoperative groups.On single regression analysis, the mean adduction angle (MAA, p= 0.007) was a better predictor of coronal plane loading in the preoperative group, while the Hip Knee Ankle angle (HKA, p=0.01) was the better predictor in the postoperative group. As the adduction moments between individual knees was variable between knees even though normalised for height and weight, the percentage improvement in PKAM (%ΔPKAM) and Add Imp (%ΔAdd. Imp) was used for further analysis. On multiple regression, the effect of change of HKA (ΔHKA) was more significant ($p = 3.5E^{-09}$) on %ΔAdd. Imp, than ΔMAA ($p = 0.01$). The correction in HKA was a significant predictor of improvement in the Add Imp ($r^2 = 0.90$) and PKAM ($r^2 = 0.50$). For every one degree correction of static alignment (HKA) a 7% improvement can be achieved in coronal plane loading (Add Imp).

On comparison of coronal and transverse plane loading data between the asymptomatic non arthritic knees and replaced knees in this group of participants, the adduction moment curve, parameters like PKAM, Add Imp and rotation moments were nearly identical, implying that articular surfaces, does not seem to have a significant effect on the regulation of its own loading. The improvement of loading with correction of alignment is likely to have an impact on wear and subsequent survivorship of the prosthesis.

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My biggest thanks go to my family and friends; who had to bear with me for the duration of this work and helped me with timely advice.

Glossory of terms

Cortical (Lamellar) bone: Cortical bone forms the cortex, or outer shell, of most bones.

Cancellous (Trabecular) bone: Cancellous bone is highly vascular and frequently contains red bone marrow where hematopoiesis, the production of blood cells, occurs.

Osteolysis: active resorption of bone matrix by osteoclasts as part of an ongoing disease process.

Force: Mass (M) × acceleration (a).

Weight: Mass (M) × acceleration due to gravity (g).

Load: is a term used in engineering to mean the force exerted on a surface or body.

Moment: Force × perpendicular distance between the line of the force and the centre of rotation.

Centre of Mass (COM): The point at which the mass is theoretically resolved to be concentrated and through which it appears to act**.**

Centre of Pressure (COP): The point of application of the ground reaction force through the foot.

Mechanical axis: The line through a segment of the body through which the weight passes.

Mechanical axis of lower limb: Line joining the centre of the femoral head with the centre of talus.

Hip Knee Ankle (HKA) angle: The angle made by mechanical axes of femur and tibia

Unicompartmental knee replacement (UKR): The knee is made up of the medial and lateral parts of the tibio femoral articulation and the patella femoral articulation. The replacement of one of these parts is referred to as unicompartmental knee replacement.

Total knee replacement (TKR): The replacement of all three parts is referred to as total knee replacement.

Survivorship: A plot of population figures against time for a group of joint replacements implanted in the same year, showing how many remain after each year, starting from year one. Death of the patient is regarded as censored data.

Contralateral: The opposite side of the body, i.e. the opposite limb.

Ipsilateral: On the same side of the body, i.e., the same limb.

Coronal Plane: The plane that divides the body or body segment into **anterior** and **posterior** parts.

Sagittal Plane: The plane that divides the body or body segment into the right and left (**medial** and **lateral**) parts.

Transverse Plane: The plane at right angles to the coronal and sagittal planes that divides the body into superior and inferior parts.

Abduction: Movement away from the midline of the body in the coronal plane. The posture or attitude of the limb would be described as **valgus**.

Adduction: Movement towards the midline of the body in the coronal plane. The posture or attitude of the limb would be described as **varus**.

Flexion: Bending of a joint, for example, when the bones comprising a joint rotate towards each other in the sagittal plane.

Extension: Straightening of a joint, for example when the bones comprising a joint rotate away from each other in the sagittal plane.

Plantar flexion: Movement of the foot away from the anterior aspect in the sagittal plane.

Internal rotation: When the distal segment is rotated medially in relation to the proximal segment in the transverse plane.

External rotation: When the distal segment is rotated externally in relation to the proximal segment in the transverse plane.

Observational gait assessment: A qualitative visual description of an individual's upper and lower extremities, pelvis and trunk motion during ambulation.

Motion analysis: Interpretation of computerized data that documents an individual's lower and upper extremities, pelvis, trunk and head motion during ambulation.

Markers: Active or passive objects (balls, hemispheres or disks) aligned with respect to specific bony landmarks used to help determine segment and joint position in motion analysis.

Active markers: Joint and segment markers used during motion analysis that emit a signal.

Passive markers: Joint and segment markers used during motion analysis that reflect visible or infrared light.

Electrogoniometer: An electrical transducer that can be attached to adjacent segments to measure a joint angle. Different designs accommodate changes in joint centre of rotation location and three dimensional motion.

Gait Cycle: The time elapsed from occurrence of one event (usually initial contact) of one foot to occurrence of the same event with the same foot.

Gait Stride: The distance between initial contact of one foot to the next initial contact of the same foot.

Stance phase (ST): The period of time when the foot is in contact with the ground.

Swing phase (SW): The period of time when the foot is not in contact with the ground.

Double support (DS): The period of time when both feet are in contact with the ground. This occurs twice in the gait cycle, at the beginning and end of the stance phase.

Single support (SS): The period of time when only one foot is in contact with the ground. In walking, this is equal to the swing phase of the other limb.

Initial contact (IC): The point in the gait cycle when the foot makes first contact with the ground. This represents the beginning of the stance phase. It is suggested that heel strike not be a term used in clinical gait analysis as in many circumstances initial contact is not made with the heel.

Step length (m): The distance from a point of contact with the ground of one foot to the following occurrence of the same point of contact with the other foot. The right step length is the distance from the left heel to the right heel when both feet are in contact with the ground.

Step period: This is the period of time taken for one step and is measured from an event of one foot to the following occurrence of the same event with the other foot and is expressed in seconds

Stride length: The distance from initial contact of one foot to the following initial contact of the same foot. Sometimes referred to as cycle length and is expressed in meters (m).

Velocity: The rate of change of linear displacement along the direction of progression measured over one or more strides and is expressed in metres per second (m/s).

Cadence: Rate at which a person walks, expressed in steps per minute.

Stance/swing ratio: The ratio of the stance period to the swing period.

Natural Cadence/Velocity: The rate of walking that is voluntarily assumed.

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Chapter 1

Introduction

Loading of the knee joint is vital to maintaining articular cartilage homeostasis and thickness (Vanvanseele 2002). Literature on osteoarthritis implicates loading as the cause for progression of osteoarthritis (Hunter 2009), which is measured by variables like peak knee adduction moment (PKAM) and angular adduction impulse (Add Imp). Static alignment parameters like Hip Knee Ankle (HKA) angle and location of mechanical axis on the tibial plateau have been shown to influence the loading of the knee and and the progression of osteoarthritis. The treatment of medial compartment osteoarthritis has included non invasive correction of alignment like unloader braces and surgical replacement arthroplasty amongst other modalities. This chapter details these associations to make a case for investigating the function and survivorship following medial unicompartmental knee replacement and the use of medial unicompartmental knee replacement as a unique surgical model that allows us to investigate the effect of articular surfaces on loading and how it is affected by alteration of alignment.

1.1 Loading and degeneration of the knee

Load borne by the articular cartilage has a significant influence on degeneration and progression of osteoarthritis. Increase in body weight increases the load supported by the knee, putting the articular cartilage of the knee under stress and consequently increasing the rate of cartilage degeneration (Lementowski 2008). Previous reports that correlate body weight and obesity with development and progression of osteoarthritis, indicate the crucial role of increased loading in development and progression of osteoarthritis in the knee (Cooper 2000, Lementowski 2008). A recent meta-analysis, suggested that patient characteristics with strong evidence for being predictors of knee OA progression are older age, presence of osteoarthritis in other joints, varus mal-alignment of the knee and obesity (Chapple 2011). The prevalence of knee osteoarthritis is reported to be 12.5% in populations whose age is greater than 45 years (Zhang 2010). It has been estimated that there is a 44.7% lifetime risk of developing symptomatic osteoarthritis in the knee (Murphy 2008). Osteoarthritis is a slowly progressing disease with the annual rate of progression reported as approximately 4% per year (Felson 1995). Knee osteoarthritis is more common in women than in men (Felson 1987).

1.2 Effect of Static alignment on loading of the knee

The static alignment in the coronal plane is represented by mechanical axis or the Hip Knee Ankle (HKA) angle. The mechanical axis which represents the line of load transmission in the lower limb is a line drawn from the centre of the femoral head to the centre of the talus. The mechanical axis drawn on full length long leg alignment film passes 4–8 mm medial to the knee joint centre and through the medial compartment of the knee during stance (Paley 2000) and consequently osteoarthritis is more common in the medial compartment of the knee than in the lateral compartment (Hurwitz 2002). The passing of the mechanical axis through the medial compartment, results in a peak force of about 3 times body weight during walking. This load doubles during stair climbing (Taylor 2004). Varus or valgus malalignment of the lower extremity can alter this relationship. Varus alignment results in an increase in load distribution across the medial tibiofemoral compartment (Tetsworth 1994). Patients with knee osteoarthritis are known to have increased loading of the medial compartment of the knee, and the role of the interaction between axial alignment and dynamic knee joint loading in osteoarthritis is well established (Baliunas 2002). A possible relationship between the incidence of early osteoarthritic changes and axial malalignment is only supported by limited evidence so far. In contrast, the correlation between the progression of early osteoarthritic changes and axial malalignment has been well established (Hunter 2009). The role of malalignment on the progression of medial compartment osteoarthrtitis has been substantiated by both conventional radiography (Cerejo 2002, Miyazaki 2002, Brouwer 2007) and magnetic resonance imaging (Cicuttini 2005) studies. Cicuttini et al. (2005) reported that the degree of varus knee angle was associated with a reduction in the volume of both femoral and tibial articular cartilage in the medial tibiofemoral compartment of the knee. Malalignment has also been shown to be a predictor for functional decline in knees with osteoarthritis and may play a role in osteoarthritis-related pain (Sharma 2001). The consensus appears to be that although malalignment has a significant effect on the progression of osteoarthritis, there is no strong evidence to indicate a definite influence on the incidence of osteoarthritis. With progressing osteoarthritis, there is cartilage damage in the medial compartment which results in alteration of knee alignment which in turn affects the distribution of loads both statically and dynamically. The body alters the gait by using compensatory mechanisms in an attempt to alter loading and manage pain.

1.3 Dynamic loading in Osteoarthritis of the knee

The alignment measures of Hip Knee Ankle (HKA) angle and mechanical axis (MA) are good measures of static alignment, but not of dynamic alignment. The parameters that measure dynamic loading have been studied extensively by various authors. Gait variables such as external peak knee adduction moment (PKAM) and external peak knee extension/ flexion moment which are measures of dynamic loading during stance have been shown to differ in individuals with knee osteoarthritis when compared to the normal population (Kaufman 2001, Baliunas 2002, McKean 2007) with the consequent intuitive implication of cause- effect. Authors have confirmed during the past two decades that, osteoarthritic knees exhibit greater peak knee adduction moments and angular adduction impulse, which are parameters of loading in the coronal plane (Schipplein 1991, Kaufman 2001, Baliunas 2002, Mündermann 2005, McKean 2007, Robbins 2008).

1.3.1 Peak Knee Adduction Moment (PKAM) is a valid proxy for loading

Increased peak knee adduction moments have been shown to reflect the loading of the medial compartment of the knee. Evidence, that increased peak adduction moment indicates greater loading on the medial compartment of the knee, has been demonstrated in healthy participants by finding a correlation between peak knee adduction moment (PKAM) and bone mineral content measured with dual energy x-ray absorptiometry (DEXA) (Hurwitz 1998). This investigation proved that greater peak external knee adduction moment was the best predictor of increased medial compartment bone mineral density when compared to lateral compartment bone mineral density measured on DEXA scans. This effect of loading on bone mineral density has been further demonstrated in studies using MRI scans (Jackson 2004). This investigation revealed that, late stance peak adduction moment was a significant predictor of medial tibial plateau bone size. These findings are in keeping with Wolff's law, which dictates that bone density and mass would change with load applied. This greater load on the medial compartment of the knee which results in the increased bone volume and density would be borne by the articular cartilage of the medial compartment. This increased loading would in turn have a bearing on cartilage degeneration and subsequent incidence and progression of osteoarthritis.

1.3.2 Increased loading (PKAM) leads to progression of osteoarthritis

Numerous authors have reported the increased risk of development and progression of osteoarthritis in knees with increased peak knee adduction moment (Schipplein 1991, Kaufman, 2001, Baliunas, 2002, Mündermann 2005, Lynn 2007, McKean 2007, Astephen 2008).

In a longitudinal study, subjects underwent initial gait analysis, and then had this repeated again at 5 years and 11 years, and underwent clinical scoring for symptoms at similar intervals. The only patient who developed medial compartment osteoarthritis was found to have had a very high adduction moment at the beginning of the investigation (Lynn 2007). Even though the investigation only had 28 subjects with very few symptomatic knees, it was evident that a high peak adduction moment is likely to lead to osteoarthritis.

Mundermann (2005) and Astephen (2008) demonstrated that peak knee adduction moments (PKAM) were higher in osteoarthritic knees. They also demonstrated that peak knee adduction moment (PKAM) was higher in the knees with more severe grades of osteoarthritis. This clearly indicates the relevance of the role for medial compartment loading, on incidence of osteoarthritis and also, on the progression of osteoarthritis once it has set in.

1.3.3 Adduction Angular Impulse (Add Imp) is a better measure of loading

Peak adduction moment (PKAM) is an indicator of load at a given instance. Adduction Angular Impulse (Add Imp) is the moment time integral of the adduction moment curve. It is more representative of the loading through the entire stance phase. In a recent series it was found that, increased adduction moment impulse was a better predictor of cartilage volume loss in the medial compartment of the knee, measured using MRI scans, than peak knee adduction moment over a 12 month period (Bennell 2011). Other authors have published the value of adduction angular impulse measurements on the progression and severity of medial compartment osteoarthritis (Kean 2012).

1.4 Alignment influences loading in medial compartment knee osteoarthritis

Static and dynamic alignment measures are important influences on the loading of the medial compartment. The effect of varus alignment on the increase in perpendicular distance of the ground reaction vector from the centre of the knee is intuitive. It has been shown that, varus radiographic alignment and adduction angle measures on gait analysis are significant predictors of peak knee adduction moment (PKAM) and adduction impulse (Add Imp), in knees with osteoarthritis (Barrios 2012).

It is clear from the above discussion that loading of the medial compartment, as measured by peak adduction moment (PKAM) and angular adduction impulse (Add Imp), is dependent on alignment of the knee. The loading has a significant influence on the incidence and progression of osteoarthritis of the medial compartment of the knee and is influenced by the alignment of the knee.

1.5 Load altering treatment for medial compartment knee osteoarthritis

Management of medial compartment osteoarthritis can be broadly classified as non-operative and operative interventions. Non-operative interventions may be further sub classified into modalities used to treat the symptoms of arthritis like, oral anti-inflammatory analgesics, viscosupplementation (hyaluronic acid), articular analgesic injections or modalities that decrease the loading through the medial compartment of the knee. Although the static and dynamic loading of the knee may be affected by these interventions, it would be logical to assume that only the dynamic loading process can be affected in a non-operative manner, as static loading can only be altered by interventions that affect the structural alignment permanently. Numerous investigators have studied various interventions in the treatment of medial compartment knee osteoarthritis by altering dynamic loading. These aim to reduce the peak knee adduction moment, to reduce the load transferred through the medial compartment of the knee, which in turn would diminish the progress of degeneration and reduce the severity of symptoms. These load-modifying interventions include bracing, footwear modifications (Kerrigan 2003, Fischer 2004), gait training (Kerrigan 2003), and quadriceps muscle strengthening (Huang 2001, Fransen 2003). Moreover, it has been shown that footwear modification may also alter the ground reaction force during walking (Light 1980, Wakeling 2003). Although these interventions when investigated with gait analysis, have been shown reliably to reduce the peak adduction moments, whether they reliably translate into significant slowing down of the arthritic process is still unknown.

Operative management of medial compartment osteoarthritis can be broadly divided into interventions that predominantly affect alignment, namely osteotomy and those that replace the articular surfaces, namely unicompartmental knee replacement arthroplasty. The osteotomies try to achieve realignment around the knee, so that loading of the medial compartment is reduced significantly. The realignment following the osteotomy may be achieved by a correction of the hip knee ankle axis, which is then stabilized using internal fixation. In this group, the realignment is fixed and a static correction is achieved.

Dynamic external fixators can be used to stabilize the osteotomy. The realignment can then be done by adjusting the external fixator at regular intervals (Fowler 1991). The realignment is assessed by Hip Knee Ankle (HKA) angle measurements made on radiographs at regular intervals. This allows precision in the correction of static alignment and the final HKA angle achieved. Whereas the HKA axis is commonly used to correct static alignment, the peak knee adduction moment (PKAM) can be used as a guide of dynamic loading, to achieve this. The endpoint of correction is fixed when the ground reaction vector passes through the centre of the knee or when the adduction moment undergoes significant reduction when compared to the initial value. The realignment osteotomies only delay the progress of osteoarthritis. As a result, most of the knees that undergo osteotomies eventually need replacement arthroplasty. Realignment with external fixators that use transosseous pins, is not as popular as internal fixation, because of the problems of pin site infections that may compromise future replacement arthroplasty.

Replacement arthroplasty involves the surgical resection of the articular surfaces and a replacement with metal and polyethylene inserts. Total knee replacement is the most common type of replacement in the knee, especially when more than one compartment of the knee is affected. In those patients where only one compartment of the knee is affected, unicompartmental knee replacement is the favoured option.

1.6 Unicompartmental knee replacements

Unicompartmental knee arthroplasty was first described by Marmor in 1973 (Marmor 1973). Although Marmor published good results, other early published series, considered the results of unicompartmental knee replacements unsatisfactory, since they were inferior to the results of Total Knee Replacements (Laskin 1978, Insall 1980). However, subsequent improvements in the indications, instrumentation and implants, established the value of unicompartmental replacement for the treatment of localised medial compartment arthritis (Koznin 1989). Unicompartmental knee replacements are available in different designs. These different designs use either a mobile or fixed bearing. In the fixed bearing design the polyethylene insert is fixed on the tibial base plate with a single articulating surface between the metallic femoral component and polyethylene insert like the Marmor and the Miller - Galante prosthesis. In the mobile bearing design, the polyethylene insert is mobile between the metal femoral and tibial resurfacing components, with the insert kept in place by soft tissue tension. This results in two articulations on the polyethylene bearing like the oxford meniscal bearing unicompartmental knee replacement. The Oxford Meniscal Bearing Unicompartmental Knee was first introduced in 1978, and was designed to allow large areas of contact between the femoral and tibial component in an attempt to lower the rate of wear and creep of the polyethylene (Goodfellow 1978).

1.7 Unicompartmental knee replacement – A unique and ideal surgical model

The medial unicompartmental knee replacement is a unique model as only the articular surface of one compartment is replaced with a metal and plastic articulation. The rest of the characteristics of the knee are unchanged as much as possible in a surgical model. This makes it a good model to assess the effect of articular surfaces on loading, while also making it the ideal model to assess the effect of alignment on loading. The other two models that could be used for the assessment of alignment on loading are Total knee replacement and Upper tibial osteotomy. The total knee replacement suffers from the problem of difference in stability as compared to native knee as the anterior cruciate ligament is sacrificed during surgery. Following upper tibial osteotomy, the knee takes nearly a year for the symptoms to settle down significantly. Part of these symptoms may be attributed to the healing at the osteotomy site which can be a significant confounding factor. Moreover the articular surfaces are still in place and may influence the loading post operatively due to pain.

1.8 Need for the study

The loading of the medial compartment replacement prosthesis may have an effect on the function and long term survivorship of the prosthesis. The first stage of the investigation (Study 1) was to assess the survivorship following medial unicompartmental knee replacements. The data from this investigation was used to assess the effect of alignment on function. The second stage of the investigation (Study 2) was to assess the gait parameters before and after medial unicompartmental knee replacements. There are no reports in literature on how the replacement of the medial unicompartmental knee replacements of the knee affects the loading parameters of the knee. There are no reports of how correction of alignment affects the loading of the prosthesis as measured by instrumented gait analysis following medial unicompartmental knee replacement arthroplasty.

1.9 Scope and Boundaries of the investigation

- This study investigates the effect of medial unicompartmental knee replacement on kinetics and kinematics of the knee. It also investigates the effect of coronal plane alignment on function as measured by Bristol Knee Score (BKS) and on the kinetics especially PKAM and Add Imp.
- The study does not investigate the effect of unicompartmental knee replacements on the kinematic and kinetic characteristics of the hip and ankle.
- The study does not investigate the effect of prosthetic design, surgical technique or wear properties of materials used in the manufacture of prosthesis.

1.10 Aims and Objectives

The overall aim of this investigation was to assess the clinical, radiological and loading (instrumented gait) parameters of medial unicompartmental knee replacements.

The objectives of this study were:

1) To assess the survivorship and function measured by Bristol Knee Score (BKS) following unicompartmental knee replacements and compare it withother published series of unicompartmental knee replacement.

2) To assess the effect of alignment on function measured by 50 point Bristol Knee score (BKS) following unicompartmental replacement of the knee. Further evaluate whether tibiofemoral angle measured on short radiographs correlates well with standard alignment parameters of HKA angle and location of mechanical axis on long leg film.
3) To assess the effect of medial unicompartmental knee replacement on the function of the patient using WOMAC Score and function of the knee using the modified Knee Society score.
4) To assess the effect of medial unicompartmental knee replacement on the time – distance parameters on gait analysis.
5) To assess the effect of medial unicompartmental knee replacement on the kinematic and kinetic parameters of the knee.
6) To analyse the effect of alteration of alignment on the peak knee adduction moment (PKAM) and Adduction Impulse (Add Imp)
7) To analyse the predictive value of alteration of alignment on medial compartment loading using regression analysis.
8) To assess whether the articular surface of the knee has any effect on regulation of its own loading?

1.11 Ethical approval

Initially ethical approval was obtained for the study from North Staffordshire Research Ethics Committee. Unfortunately the study had to be transferred to Royal Derby Hospitals due to unforeseen circumstances and this was done following approval from the Research and development (R&D) department of the Royal Derby Hospitals and the relevant Ethics committee. Ethical approvals, participant information sheets and consent forms may be found in Appendix section of the thesis.

1.12 Structure of the thesis

This thesis is divided into two parts. The first part consists of an investigation of function and survivorship of unicompartmental knee replacements. This was set up as a retrospective study with particular emphasis on the effect of alignment on function (Study 1).

The second part of the thesis consists of clinical scoring, alignment measurement, preoperative and postoperative gait analysis in knees that have undergone medial unicompartmental knee replacements. The differences in kinetic and kinematic parameters were assessed, to analyse the effect of replacement of the articular surface. The effect of correction of alignment on kinetic parameters was assessed as well (Study 2).

The relevant literature is reviewed in the appropriate sections as the literature for study 1 and study 2 were very dissimilar.

The thesis is divided into 10 chapters.

Chapter 1: *Introduction*; This chapter outlines the rationale behind the investigation making a logical sequence of arguments that has been used as the basis for study 1 and study 2. The biomechanical factors that contribute to the progression of arthritis especially loading are discussed. The parameters that can be used as proxy for medial compartment loading, namely peak knee adduction moment (PKAM) and the angular adduction impulse (Add Imp) are discussed briefly. The effect of alignment on PKAM and Add Imp and thus on the progression of medial compartment osteoarthritis is discussed. The treatment for medial compartment osteoarthritis and why the medial compartment replacement arthroplasty is an ideal and unique surgical model for the purpose of this investigation is discussed.

Chapter 2: *Unicompartmental knee replacement*; This chapter discusses briefly the history of medial unicompartmental knee replacement arthroplasty, its evolution into its present form and the relative merits of fixed bearing and mobile bearing components. A brief discussion of the various reports on the long term survivorship and analysis of the reasons for failure and longevity of some examples of individual prosthesis is discussed.

Chapter 3: *Study 1. Reports I & II*; A retrospective analysis of 94 patients who had unicompartmental knee replacements done under the care of a single surgeon was done

(Report 1). Report II analyses the role and effect of alignment on function and survivorship in greater detail. This investigation revealed a significant relationship between alignment and function.

Chapter 4: *Gait analysis*; Chapter 4 discusses the history and available technology behind gait analysis. The relative merits of marker systems are discussed. The kinetic and kinematic parameters especially the loading parameters like the peak knee adduction moment and angular adduction impulse and the literature relevant to the investigation are discussed in detail.

Chapter 5: *Outcome measurement following unicompartmental knee replacement*; Chapter 5 discusses the importance and characteristics of outcome measures following unicompartmental knee replacement arthroplasty. The WOMAC and the modified knee society scores are discussed in detail.

Chapter 6: *Methods - Study 2*; Methods for study II namely, clinical scoring, radiological analysis, gait analysis and statistical analysis are discussed.

Chapter 7: *Results - Study 2*; The results of study 2, including clinical scores, differences in alignment, the effect of alignment on loading (PKAM & Add Imp), the effect of correction of static alignment on the reduction of loading of medial compartment and the predictive value of correction of HKA on loading are presented in this chapter. The effect of replacement arthroplasty on the time distance parameters and kinematic parameters are presented. The reliability between measures and the standard error of measurement was calculated for each gait and radiological parameter measured, and this is presented in this chapter.

Chapter 8: *Discussion*: The results of study 2 are discussed and compared with the results of other reports on findings of gait analysis. It also discusses the relative merits and demerits of alignment measures used in this investigation. There is a discussion on the variation in static alignment parameters following unicompartmental knee replacements. The efficacy of kinematic alignment parameters and comparison with the static alignment measures are discussed.

Chapter 9: *Does articular surface regulate its own loading?* This is presented as a separate chapter as the premise for this question and analysis of data are completely different to rest of the analysis. Although the data from the gait analysis is used, it was felt that the context and the groups analysed necessitated a separate chapter.

Chapter 10: *Conclusions*; Conclusions drawn from this investigation are recorded in this chapter. Limitations of research, directions for future work and implications for surgical practice are discussed in this chapter.

Appendices: The ethics committee approval, approval for site transfer, patient information sheet, consent form, WOMAC licence, statistical evidence for normal distribution of data are presented in this section.

Chapter 2

Unicompartmental Knee Replacement

2.0 The surgical model – medial unicompartmental knee replacement

This section details the evolution of prosthetic design and surgical technique with unicompartmental knee replacements. It includes review of literature on survivorship and effect of alignment on function in unicompartmental knee replacement which is relevant to study 1. The reports on Study 1 are, one on survivorship following medial unicompartmental knee replacement and another on the effect of alignment on function. The survivorship and function is reported separately as the function has a significant impact on whether unicompartmental knee replacements is an appropriate model for the assessment of loading, as this is contingent on the unicompartmental knee replacement improving the symptoms of arthritis significantly. The effect of function is discussed separately as this is part of the assessment of the effect of alignment on loading of the medial compartment of the knee.

2.1 Unicompartmental knee replacement – Brief history

The knee is described as having three compartments, medial, lateral and patellofemoral compartments. Unicompartmental knee prosthesis replaces either of medial or lateral compartments which are arthritic. The unicompartmental knee replacements have evolved dramatically in the last fifty years to reach its present form and reliability. The earliest unicompartmental knee prostheses can be traced to tibial hemiarthroplasty implants like the MacIntosh prosthesis introduced in 1964 (McIntosh 1972). The MacIntosh prosthesis had a smooth, concave shape, with a flat serrated under surface. Around the same period the metal-resurfacing McKeever prosthesis was developed (Scott 1985). The McKeever prosthesis had a T-shaped fin on the under surface which increased the stability following implantation. Although these early designs showed good early to intermediate results in 70% to 90% of patients, a revision rate greater than 50% at 10 years following surgery, along with the advent of improved designs with longer survivorship, resulted in them losing popularity (McIntosh 1972, Scott 1985, Springer 2006).

The next step in the evolution of unicompartmental knee replacement happened alongside the development of early total knee replacement designs. The commonly used early Implants such as the St. Georg Sled (Waldemar Link, Hamburg, Germany), the Polycentric Knee (Protek, Berne, Switzerland) and the Marmor (Smith & Nephew, Memphis, TN, USA) were developed and implanted during this period (Engelbrecht 1971, Gunston 1971, Marmor 1973). These designs were used either in a unicondylar or bicondylar mode depending on the extent of arthritis in the knee. These replacement prostheses used bone cement at the time of implantation. Bone cement is polymethylmethacrylate and is used as a grout between the prosthesis and trabecular bone.

The unicompartmental knee replacement designs included a femoral component, a tibial component and a polyethylene articulating spacer. The articulating polyethylene spacer is either fixed onto the prepared tibial plateau, or onto the metal tibial base plate which is fixed on to the bony tibial plateau or it is mobile on the metal base plate. Amongst the fixed bearing unicompartmental knee replacements, the most successful were the ones with flat tibiae on round femur designs. These designs were predominantly unconstrained, which meant that the contact area between the metal femur and the polyethylene tibia was smaller than constrained versions, resulting in increased wear and polyethylene debris. The use of conforming articulations would increase the surface area of bearing articulation and decrease the wear, but this would increase the constraint on the prosthesis during the range of motion on the knee (Kinematic conflict). Although the introduction of more conforming bearing surfaces reduced the problem of wear, it introduced the problem where the rotational stresses were transferred to the bone prosthesis interface with resultant risk of loosening (Engh 2001). This problem was solved using a mobile bearing that uncoupled the torsional stresses at the interface by having a flat tibial component that articulated with the flat under surface of the polyethylene bearing (Buechel 1986, O'Connor 1996, Callaghan 2000). The Oxford unicompartmental knee replacement (Biomet Orthopedics, Warsaw, USA) is a very popular mobile bearing unicompartmental knee replacement in the United Kingdom. The oxford prosthesis was designed by John Goodfellow and John O'Connor to be used as a bicondylar device, and was first used in a patient as a unicompartmental device in 1982 (Goodfellow 1988). The design comprises of a spherical metal femoral component and a flat tibial base plate. A polyethylene bearing, concave and conforming on the femoral side and flat on the tibial side is inserted between the metal prosthetic components. The driving factor behind these modifications were to address the problem of polyethylene wear debris and its role in osteolysis (softening of bone) and subsequent loosening which became a significant problem in all forms of replacement arthroplasty (Goodman 1992, Engh 2001).

In general, the design characteristics of unicompartmental knee replacements have not undergone great changes over the past 30 years. Although the use of bone cement at the bone – prosthesis interface at the time of implantation, remains very popular, uncemented systems are available in the market and are becoming increasingly popular. The development of mobile-bearing designs and use of modular tibial components have increased the versatility and precision of unicompartmental replacement surgery. Features such as fins or pegs, have been incorporated into femoral component designs to optimize rotational stability immediately following implantation. These features allied with improvement in instrumentation to prepare the bony bed for implantation of prosthesis have increased the precision and subsequent survivorship.

2.2 Categorisation of unicompartmental knee replacements

Unicompartmental Knee replacements can be broadly categorized based on,

I) bony preparation (resurfacing or inset technique)

II) mode of implant fixation (Uncemented or Cemented)

III) polyethylene bearing (fixed-bearing or mobile-bearing).

2.21 Resurfacing Technique

Resurfacing techniques as the name implies involves the replacement of the arthritic surface with the prosthesis. It uses instruments in preparation of bone surfaces, crucially retaining the subchondral bone. This category of prosthesis includes the original Marmor, the St. Georg, and the Repicci (Biomet, Warsaw, IN) designs. Resection of the optimal amount of bone for stable fixation in a precise manner while achieving optimal alignment can be challenging because of limited use of guides in this method. The St. Georg prosthesis, which has been in clinical use since 1969 (Engelbrecht 1976) consists of a biconcave metal femoral component and a flat, cemented, all-polyethylene tibial component. The Marmor prosthesis had a stainless-steel femoral component and an all polyethylene tibial component and was first implanted in the early 1970s (Marmor 1973). The Repicci prosthesis consists of a cobalt-chrome femoral component and an all-polyethylene tibial component. The femoral component had a single fixation peg attached to a sagittally oriented fin in order to improve rotational stability (Repicci 1999). The bony surfaces are hand prepared with burrs, while maintaining the subchondral bone for support.

2.22 Inset Technique

Inset designs use a femoral preparation technique similar to that used in Total Knee Replacement Arthroplasty, where guides are used to make bony cuts on the femoral and tibial sides. The cancellous bone surface is prepared to exactly match the inner dimensions of the components resulting in a large contact area between implant, cement and bone. Examples of inset prosthesis are, the Miller-Galante prosthesis (Zimmer, Warsaw, Ind, USA) which has had promising results and, the Porous Coated Anatomic knee (PCA; Stryker, Mahwah, NJ, USA), which had suboptimal clinical results in the early reviews (Argensen 2002, Bergenudd 1995, Riebel 1995, Lindstrand 1992, Hodge 1992).

Figure 2.1 Fixed bearing (left) & mobile bearing (right) unicompartmental knee. (adapted from Zimmer and Biomet surgical techniques manuals 2009)

2.3 Mobile bearing unicompartmental knee replacement – Oxford UKR

The Oxford mobile bearing unicompartmental knee replacement has become very popular since it became available in the eighties. Although the Oxford unicompartmental knee replacement (Biomet Orthopedics, Inc, Warsaw, Ind, USA) was designed for bi condylar use, this was put to clinical use as a unicompartmental device only in 1982 (Goodfellow 1988). The design comprises a spherical metal femoral component and a flat tibial base plate with a conforming but unconstrained polyethylene bearing. The polyethylene bearing is mobile at the femoral and tibial side as well (Figure 2.1).

As discussed previously, polyethylene debris from bearing surface wear had become a significant concern, as it had been linked to osteolysis and early implant failure, particularly in unicompartmental knee replacements (Goodman 1992, Engh 2001). The early design of oxford unicompartmental knee replacement aimed at increasing the congruency between the prosthesis and bearing surfaces to reduce wear (O'Connor 1996). However, congruent surfaces imply a high level of articular surface constraint introducing a kinematic conflict which results in significant torsional stresses at the implant bone interface, especially when the individual components are fixed relative to each other (Goodfellow 1978, Buechel 1986). This kinematic conflict was resolved by the use of a mobile bearing in the knee replacement which creates conforming surfaces at the articulations but allows the knee to move as dictated by the ligaments and muscles around the knee much like the natural knee would (O'Connor 1996, Buechel 1986).

The popular LCS (Low Contact Stress) mobile bearing total knee replacement design addressed the problem with a two - fold modification, which included the mobile polyethylene bearing and a differential radius of curvature in extension and flexion. The radius of curvature was constant in the coronal and sagittal planes in extension and was significantly larger in extension than in flexion (Buechel 2002). This was different from the single radius of curvature in flexion and extension of the femoral component of both the oxford unicompartmental knee and the total knee prosthesis. The Oxford meniscal polyethylene bearing is held in place between the spherical femoral articular surface and flat tibial articular surface by tension in the soft tissues across the bearing. The potential advantage of this design is a conforming concave femoral– polyethylene interface with a large contact area (nearly six square centimetres) and a similarly conforming flat tibial-polyethylene interface with a large surface area. Moreover apart from allowing unconstrained motion at the interfaces, it has further contributed to extremely low wear measurements, in the order of 0.01 to 0.03 millimetres per year (Psychoyios 1998). Thus the choice of component geometry, together with a freely mobile meniscal bearing, reduces polyethylene wear and allows the soft tissues to reproduce near normal kinematics and kinetics of the knee (Goodfellow 1978, O'Connor 1989, O'Connor 1996).

The first Oxford knee prosthesis was used as a bicondylar design to replace both compartments in the treatment of rheumatoid arthritis or osteoarthritis. However, early results showed that an absent or severely damaged anterior cruciate ligament (ACL) at the time of surgery was an important determinant of early implant failure (Goodfellow 1978, Goodfellow 1986). At the same time, it was observed that if the anterior cruciate ligament was intact, osteoarthritis was usually limited to the medial compartment of the joint and came to be considered the primary indication for the use of the mobile-bearing prosthesis as a medial unicompartmental replacement (Goodfellow 1986, White 1991).

Although the components of the Oxford unicompartmental knee replacement have maintained the same fundamental design features since inception, it has evolved into the present form to make it more versatile and precise for implantation. The oxford phase1 prosthesis had only one size of femoral component and five sizes of tibial component, and there were very few special instruments. The cuts for the femoral component were made with a cutting block, which allowed for the removal of three slivers of bone to fit the shape of the nonarticular surfaces of the component (Goodfellow 1978). The tibial cut was made with an extramedullary jig. The flexion and extension gaps were measured with gap gauges of the same thickness as the meniscal bearings (3.5 to 11.5-mm thick, in 1-mm increments). The femoral and tibial components were cemented into place, and the procedure was completed by inserting the appropriately sized polyethylene bearing.

The phase 1 femoral component did not allow resection of small increments of bone to balance the flexion and extension gaps intraoperatively in a precise manner. The phase 2 implant was introduced, with a spherically concave inner surface of the metal femoral condyle and instrumentation to achieve perfect flexion and extension balance. The femur was prepared with an end-cutting bone mill, rotating around a spigot in a drill hole in the condyle. The mill shaped the distal end of the femur to a spherical form and allowed for removal of bone from the condyle in 1-mm increments, controlled by sequentially advancing the mill on the spigot. The extension gap could then be increased until it precisely matched the flexion gap constantly measuring the gaps with gauges.

The phase 1 and phase 2 implants were implanted through a midline surgical approach very similar to that used for total knee replacement arthroplasty. In 1998, the phase 3 Oxford device was introduced with new instruments and an increased range of component sizes to facilitate its implantation through a smaller incision, following the increased popularity of minimally invasive implantation with the Repicci prosthesis. The core features of the implant geometry and femoral bone resection techniques (milling) were preserved. The aim was to improve the short-term advantages, such as rapid rehabilitation and a better range of motion, while preserving those features of the design believed to have contributed to the survival of the implant in the longer term (Keys 1999).

2.4 Review of literature on survivorship in Unicompartmetal Knee Replacements

Survivorship analysis is a powerful tool in the study of the longevity of prosthesis. Survival analysis is a method of analysing data from patients with different lengths of follow-up, allowing cases to enter and be withdrawn from a trial or database at any stage and for whatever reason. A fundamental assumption in survival analysis is that patients who are lost to follow-up and patients who die have the same failure rate as those who complete the trial or remain successful. Symptomatic aseptic loosening is defined as the failure in replacement arthroplasty. There are two general types of analysis for survival information: actuarial and Kaplan-Meier. An actuarial analysis should be performed when the actual date of a survival event is unknown. Kaplan-Meier analysis is used when the actual date of the end point is known. End points not reached are treated as censored at the date of last follow-up for the analysis. The commonly used survivorship analysis method in arthroplasty reports is the Kaplan – Meier method, even though the actual date of symptomatic aseptic loosening is not precisely defined.

Fixed and mobile bearing unicompartmental knee replacements have shown good clinical results and survivorship reported by various authors. This has been shown in the table below.

Table 2.1 Survivorship following unicompartmental knee replacements

Authors	Year	Implant	Age at Op	FU (years)	No: at start	No: at FU	Survivorship
Scott et al	1991	Brigham (J&J)	71(41-85)	10(8-12)	100	64	87%
Heck et al	1993	Compartmental I &II (Zimmer)	68.2(22-92)	6(1-15)	294	250	91%
Cartier et al	1996	Marmor (Richards)	65(28-82)	12(10-18)	207	60	93%
Ansari et al	1997	St. Georg Sled(Link)	70(46-93)	4(1-17)	461	437	88%
Murray et al	1998	Oxford(Biomet)	70.7(34-90)	7.6(1-13.8)	143	109	97%
Berger et al	1999	Miller Galante(Zimmer)	68(51-84)	7.5(6-10)	62	51	98%
Squire et al	1999	Marmor (Richards)	70.9(51-94)	18(15-22)	140	48	84%
Svard et al	2001	Oxford(Biomet)	69.6(50-85)	12.5(5-15)	124	94	95%
Ashraf et al	2002	St. Georg Sled(Link)	69(51-92)	9(2-21)	88	83	83%
Argenson et al	2002	St. Georg Sled(Link)	66(35-88)	5.5(3-9)	171	160	94%
Pennington et al	2003	Miller Galante(Zimmer)	54(35-60	11(5-13)	46	45	92%
Naudie et al	2004	Miller Galante(Zimmer)	68(39-87)	10(3-14)	113	97	90%
Rajasekar et al	2004	Oxford(Biomet)	70.2(58-87)	5.8(2-12)	135	96	96%
Steele et al	2006	St. Georg Sled(Link)	67(36-85)	14.8(10-29)	203	134	80%

On closer analysis, the reasons for variation in survivorship between different designs become apparent. Among the latter fixed bearing designs, the early failure of the Porous Coated Anatomic (PCA) knee is interesting and instructive. In the nineteen eighties, osteolysis and loosening of the prosthesis came to light and was becoming a significant problem. As the loosening was occurring at the bone cement interface, this phenomenon was attributed to the bone cement becoming brittle and, fracture of the cement mantle with time, following implantation. The subsequent formation of debris was believed to lead to an inflammatory reaction, resulting in osteolysis and implant loosening. This was called cement disease at the time and prompted efforts to limit the use of bone cement in replacement arthroplasty (Hungerford 1987). Although inflammatory osteolysis was studied extensively and has been found to be secondary to polyethylene wear debris, the philosophy of uncemented implants continued to gain ground. Unsurprisingly, osteolysis and loosening has been seen in uncemented implants as well. Although wear particle sources can be manifold, the polyethylene wear debris is considered to be most potent in the generation of osteolysis and loosening. The PCA prosthesis was uncemented. The geometry of the polyethylene insert of the PCA was conforming to increase the area of contact. Unfortunately this also caused a constraint in range of motion which resulted in the femoral component, riding up the central slope of the tibial component. Although the conforming surfaces were introduced to decrease wear, if the area of articulation did not remain large right through the kinematic profile of the knee, increased loading through a smaller area can result in increased wear, like it did on the central slope of the tibial insert (Bergenudd 1995). The uncemented fixation of the PCA prosthesis meant that the increased shear stresses secondary to the constraint introduced by the conforming surfaces did not allow the prosthesis to osseointegrate (integrate with the bone), resulting in high early loosening rates. The polyethylene insert of the Porous Coated Anatomic prosthesis was heat treated to decrease friction and to increase wear resistance. As the heat treatment was thought to increase wear resistance, thinner polyethylene inserts were used. Heat treatment unfortunately, resulted in pitting and delamination of the polyethylene. This resulted in subsurface delamination and accelerated wear (Bergenudd 1995). The early failures of the PCA prosthesis were reported by other authors as well (Riebel 1995, Lindstrand 1992, Hodge 1992). It appears that even though the design modifications were well conceived when analysed individually, the combination proved unfortunate. The conforming polythelene design to increase the area of contact resulted in a constraint in the range of motion, which led to edge loading or point loading and dramatic increase in wear rate. The constrained design also introduced shear stresses at the implant bone interface compromising the process of osseointegration.

Amongst the earlier successful designs were the St. Georg Sled, Marmor and Repicci designs. In the reports on the St. Georg Sled Uni compartmental knee replacements (Ansari 1997, Steele 2006), the Marmor unicompartmental knee replcements (Marmor 1988) and the Repicci unicompartmental knee replacements (Romanowski 2002), the commonest cause of conversion to total knee replacement was found to be progression of arthritis in the unaffected compartments. Although the causes for this can be manifold, overzealous correction of alignment, where the mechanical axis was shifted to the unaffected lateral compartment at the time of index surgery was considered to be the avoidable surgeon controlled issue (Kennedy 1987, Marmor 1988, Ansari 1997, Steele 2006).

The next common cause of conversion to total knee replacements in these designs was wear of the polyethylene with subsequent osteolysis and loosening. Although polyethylene wear is an inevitable consequence of replacement arthroplasty where a metal – polyethylene bearing is used, imprecise positioning of implants, resulting in point or edge loading on the polyethylene insert, results in significant amount of wear. The wear rate in fixed bearing unicompartmental knee replacements was particularly susceptible to malpositioning of prosthesis. Although in theory, the mobile bearing designs would be less likely to suffer from problems of wear, malpositioning of implants can lead to problems of bearing dislocation. As a result, it is apparent that precise positioning of implants is crucial to obtaining good results with unicompartmental knee replacements. The problem of wear has been historically accentuated by the use of thinner inserts, like the 6mm insert in the Marmor prosthesis (Marmor 1988). The 6mm polyethylene insert is 4mm at its thinnest, making it susceptible to catastrophic failure as the thickness reduces with polyethylene wear (Bartel 1986). The use of thicker inserts appeared to give some protection over the problem of wear and loosening (Marmor 1988, Squire 1999). The other causes of revision included poor patient selection like severe fixed deformity of the knee, instability and obesity (Marmor 1998, Steele 2006).

The weight of the patient has been reported to affect long term survivorship following unicompartmental knee replacements (Heck 1993), with higher revision rates associated with weight greater than ninety kilograms. A weight of greater than eighty two kilograms has been quoted by some authors as a contraindication for unicompartmental knee replacement (koznin

1989). Although good survivorship has been reported in heavier patients in subsequent series (Pennington 2003), unicompartmental knee replacements are not the preferred option in these patients, as it does not allow alteration alignment to the same extent as total knee replacements at the time of operation. Total knee replacement appears to be the preferred option as it can be placed in alignment with the mechanical axis passing through the centre of the knee which is considered optimum for survivorship.

Modern day medial unicompartmental knee replacements have shown good survivorship at 10 years by numerous authors (Table 2.1) who report good outcomes in carefully selected patients.

The review of literature on survivorship has revealed good survivorship of both mobile bearing and fixed bearing unicompartmental knee designs. The analysis of designs which failed early on, imply the importance of wear and subsequent osteolysis in fixed bearing designs. The survival rates are heavily influenced by the loading conditions as evidenced by the lower survival rates in patients greater than 90 kgs that may hasten wear, osteolysis and loosening.The effect of appropriate alignment and its effect on less congruent articulation and the effect this has on these prostheses has been alluded to in the literature on survival analysis. As this forms a major part of the thesis it is discussed in detail in the following section.

2.5 Review of literature on alignment in arthritis and following knee replacement

The importance of alignment of the knee joint and the effect of alignment on progression of arthritis and its importance in long term survival of total knee replacements are discussed. Alignment is a significant factor in the loading of the tibial plateau in arthritic knees resulting in the progression of osteoarthritis (Sharma 2001) and in replaced knees. Alignment following total knee replacement, has received a lot of attention as it is believed to have a significant impact on rates of failure. The mechanical axis of the limb in the coronal plane and its effect on function and survival has been reported more than any other alignment parameter (Vince 1989, Jeffrey 1991). Most of the literature has concentrated on the importance of alignment on the coronal plane as this has been the parameter traditionally measured on the anteroposterior radiograph. The mechanical axis is the most commonly studied alignment parameter. The mechanical axis of the lower limb is defined in different ways. It can be measured as the angle between one line drawn from the centre of the femoral head to the deepest part of the femoral notch at the knee, with a second line drawn from the midpoint of the tibial plateau to the midpoint of the inner extension of the tibio-talar joint – tibiofemoral angle (TFA). Or else it can be described as the area of the tibial plateau through which a line from the centre of the femoral head to the centre of the talus passes (Kennedy 1987). The apparent benefits of achieving a neutral mechanical axis (angle of 0° or the mechanical axis passing through the centre of the tibial plateau) of the lower limb during total knee replacement surgery has encouraged surgeons and manufacturers to invest time and resources into achieving this alignment target (Oswald 1993).

There are conflicting reports regarding the importance of mechanical alignment following total knee replacement surgery. Tibiofemoral angle of greater than 3.9 degrees of varus was reported to result in increased incidence of tibial sided failure (Berend 2004). A further report from the same group of authors reported that risk of revision increased seven fold if the prosthesis was placed in less than 2.4 degrees of valgus (overall varus alignment of limb) or fourfold increase in revision rates if the prosthesis was placed in 7.2 degrees of valgus (valgus alignment), with 4.8 degrees valgus defined as neutral alignment (Fang 2009). This view has been countered by a report at 15 years' follow up of nearly four hundred total knee replacements, which found the revision rates between the group that had well aligned total knee replacements and the outlier group which did not have well aligned knee replacements was not statistically significantly different (Parratte 2010). Although the different authors did not find the threshold of 3 degrees of valgus (5 degrees of valgus being neutral) as significantly affecting revision rates, greater varus alignment are considered to result in significantly greater risk of failure.

It is apparent that alignment has a significant role in the progression of arthritis and and is a significant contributing factor in prosthetic survivorship following total knee replacement. The effects of alignment in medial unicompartmental knee replacements have been described in greater detail in the subsequent section.

2.6 Review of literature on the effect of alignment in unicompartmental knee replacement

A systematic review of literature was completed. The Medline® Database was searched using the combination of the following keywords: alignment, medial unicompartmental, medial unicondylar and knee. Any papers that contained these keywords in the title, keywords or the abstract were retrived for analysis.

Use of terms medial unicompartmental or unicondylar knee was found in 102 articles, on combining alignment with these terms, 16 articles were included. Of these articles, ones relating to patellofemoral joint, rotational alignment, lateral unicompartmental knee replacement were excluded. Of the remaining 12 papers two were articles on study 1 (Reports 1&2). All these were carefully reviewed and have been cited in at various points in the previous and subsequent sections.

The importance of alignment after total knee replacement has generally been transposed to the practice of medial unicompartmental knee replacement (Kennedy 1987, Cartier 1996, Ridgeway 2002, Keene 2006).The importance of alignment has been questioned by some authors, suggesting that minor mal-alignment will not affect outcome (Gulati 2009, Mullaji 2011) but major mal-alignment would (Larsson 1988). Significant malalignment could potentially result in poor outcome resulting in revision surgery (Kennedy 1987).

Table 2.2 Summary of findings on alignment

Author	year	Number	Method	Implant	Alignment Effect
Clement	2011	49	Clinical	mobile	Consequential
Mullaji	2011	122	Radiological	mobile	Not
Mercier	2010	49	Radiological	mobile	Consequential
Gulati	2009	160	Clinical	mobile	Not
John J	2009	94	Radiological	fixed	Consequential
Collier	2007	81 retrievals	Radiological	fixed	Consequential
Perkins	2002	40	Radiological	fixed	Consequential
Ridgeway	2002	185	Radiological	fixed	Not
Emerson	1992	69	Radiological	both	Consequential

It is evident from the above table that the opinion on whether significant varus malalignment defined as less than 174^{o} translates into significant effect on revision rates or other consequences is divided. The early literature on the effect of alignment on fixed bearing unicompartmental knee prosthesis may not necessarily be strictly applicable to mobile bearing unicompartmental knee replacements. The mechanism of loosening following mal-alignment is very different between total knee replacements and unicompartmental knee replacements. Malalignment following total knee replacements may result in eccentric loading of the polyethylene bearings, which would increase wear and risk of loosening. In total knee replacements, ligament balance also appears to be equally important in preventing phenomena like condylar lift-off that can result in accelerated wear (Dennis 2001). In unicompartmental knee replacements, whatever the alignment of the knee, as long as the tibial baseplate is perpendicular to the tibia, the loading of the polyethylene bearing occurs at the centre of the prosthesis in the mobile bearing prosthesis. The only concern in cases of significant varus being that the adduction moments will be high, which will increase loading and may increase the risk of loosening and revision in the long term. Although this is the case in extension, it is said to be less likely to be a problem when the knee is flexed as the varus is partially corrected in flexion (Gulati 2009). As unicompartmetal knee replacements are done only in patients with functionally intact ligaments and near normal kinematics, the likelihood of eccentric loading of the prosthesis is fairly slim as a result. The aim is to restore the alignment to the alignment prior to development of arthritis especially in mobile bearing unicompartmetal knee replacement arthroplasty. As the alignment prior to development of osteoarthritis is not known, it is inferred from the tension of the ligaments at the time of surgery.

As the philosophy behind under correction in unicompartmental knee replacement is appealing, majority of the authors of unicompartmental knee replacement literature have advocated relative under correction of the alignment of the knee, as it is believed that overcorrection increases the risk of failure by progression of the disease in the unaffected compartment which is of greater concern and there is less of a risk of overcorrection if undercorrection was the aim in the first place (Kennedy 1987). Although this concept is intuitive it has been disputed by some authors (Ridgeway 2002) who did not find that revision rates correlated with undercorrection. Most authors on fixed bearing prosthesis have suggested residual varus (under correction) inorder to avoid overcorrection at all costs. In the mobile bearing unicompartmental knee replacement residual varus is a consequence of the philosophy where in the alignment is left in position of optimum soft tissue tension.

Chapter 3

Study 1: Retrospective analysis of unicompartmental knee replacements done by a single surgeon over a period of 17 years.

Aspects of this chapter has been published in the following reports:

Report I

John J, Mauffrey CM, May PC, 2011. Unicompartmental knee replacements with Miller – Galante prosthesis. 2 to 16 year follow up of a single surgeon series. International Orthopaedics. 35 (4): 507-13.

Report II

John J, Kuiper JH, May PC, 2009. Age at follow-up and mechanical axis are good predictors of function after unicompartmental knee arthroplasty. An analysis of patients over 17 years follow-up. Acta Orthopaedica Belgica.75 (1): 45-50.

This chapter reports the results of function and survivorship in patients reviewed as part of the retrospective analysis of unicompartmental knee replacements (Study 1). The function and survivorship is presented as a separate report as this is an assessment of whether the surgical model (medial unicompartmental knee replacements) is appropriate for the assessment of loads through medial compartment of the knee.

3.1 Introduction

Study Type: A retrospective review of function, and radiological appearance at follow up of unicompartmental knee replacements, done by a single surgeon (PC May) was done.
Duration: 17 years. The study included all patients treated surgically between 1989 and 2006.
Site: All patients were treated at the Princess Royal Hospital Telford, United Kingdom.
Prosthesis: All patients had a Miller-Galante Unicompartmental Knee Replacement (Zimmer Warsaw, Ind, USA). The Miller-Galante arthroplasty system consisting of a cobalt-chromium alloy femoral component and a titanium alloy tibial tray was used in all patients.
Surgical Procedure: A standard midline incision and medial parapatellar arthrotomy was used to implant the prosthesis. The patella was translated and the individual patello femoral and tibiofemoral compartments were inspected. In the presence of deficient anterior cruciate ligament a total knee replacement arthroplasty was performed.
Indications for surgery: The replacement was performed for symptomatic unicompartmental osteoarthritis. Fibrillation or marginal erosions of the opposite compartment and/or patellofemoral compartment were not a contraindication, as long as asymptomatic.
Contraindications for surgery: Patients with insufficiency of ACL, fixed flexion deformity of more than 15 degrees, fixed varus deformity, night pain, synovitis and other haematological parameters suggestive of inflammatory arthritis were treated with total knee replacement.

3.2 Patients and methods

94 knees (70 patients) were replaced. Of these 60 were in men and 34 in women. There were 66 unilateral, 18 staged bilateral procedures and 5 (10 knees) bilateral procedures done at the same sitting. Of these 18 patients (27 knees) died and five were lost to follow-up. The state of the knee in deceased patients was determined from hospital and general practitioner records establishing if a further surgical procedure had been carried out. Seven knees (six patients) were revised either by the same surgeon or elsewhere. The remaining 41 patients (56 knees)

attended a follow-up clinic. They were assessed both clinically and radiologically. The clinical assessment was done using the 50 point Bristol knee score.

3.3 Radiological assessment

All patients had a long leg view to assess the mechanical axis, apart from the routine anteroposterior and lateral radiographs of the knee. The mechanical axes (Fig. 3.1) of limbs were assessed with long leg views. A line from the centre of the hip was drawn and the zone of intersection on the tibial plateau (Fig 3.2) was recorded for each knee as described by Kennedy and White (1987). Appropriate alignment was defined as the mechanical axis passing through the central zone or any of the zones medial to the central zone in medial unicompartmental knee replacements (central or varus) and central or lateral in lateral unicompartmental knee replacements (central or valgus).

Figure 3.1.Mechanical Axis

Figure 3.2 Tibial zones

3.4 Study 1 Report 1

The introduction and review of literature for this report has been discussed previously.

3.4.1 Statistical method for survival analysis

Kaplan – Meier analysis was done using SYSTAT vs. 11 (Systat Software Inc, Point Richmond, CA, USA). Rate of survival was determined using Kaplan-Meier survival analysis using revision for symptomatic aseptic loosening of the prosthesis for any cause as the endpoint.

3.4.2 Results

The data was confirmed to be parametric using histograms, q-q plots and Kologomorov – Smirnoff statistic (Appendix F). The mean age at surgery was 66.54 years (48 – 73 y, SD =6.9 y). The mean follow-up was 10.8 years (range 2 –16 y, SD= 4.8y). The mean total Bristol knee score at follow-up was 43.61 (range: 28–50, SD= 6.44). The mean functional score was 16.3 (9–20, SD= 3.86). A total of 88% of patients had good or excellent total score and 73% patients had good or excellent functional score. Fifteen patients had a fair/poor functional score while only eight had their total score in the fair/poor category. This discrepancy can be attributed to increasing age, medical co-morbidity and disease in patients with otherwise well implanted joints. The mean range of movement at follow up was 110.6° (80–130°). Overall, 25 (45%) of the knees had no pain, 24 (43%) mild or occasional pain and 7 (12%) moderate pain. All patients stated that they had improved after the procedure. Seven (7.4%) patients required blood transfusion. There were no deep infections. Three knees had a superficial wound infection which responded to antibiotics. On radiological analysis, five (9%) knees showed lucent zones on the tibial side. These were <2 mm, stable and non progressing. The alignment in fifty knees (89%) was appropriate, i.e. central/varus in medial unicompartmental knee replacements and central/valgus in lateral unicompartmental knee replacements. Of the fifty knees in appropriate alignment, five knees had the mechanical axis passing through the appropriate side of the centre of the tibia but outside the tibial plateau itself. This increases the moment arm resulting in a higher adduction moment and possible wear of the prosthesis. In four medial unicompartmental knee replacements, the mechanical axis passed through the lateral compartment, suggesting inadvertent overcorrection. The ideal alignment is when the mechanical axis passes through the replaced half (or the central portion of the tibial plateau being replaced). Seven knees, in total, underwent revisions for either progression of arthritis of the non-replaced compartment or loosening of the prosthesis. Only two medial unicompartmental knees were revised for loosening, at the tenth and the 13th year, respectively. The survivorship at ten years was 94% and at 15 years was 87%. The lateral unicompartmental knee replacements did significantly worse, especially in women. In our series all patients who underwent lateral unicompartmental knee replacements were women.

Figure 3.3.MA through replaced compartment. **Figure 3.4.MA through centre of knee**

Three of the lateral unicompartmental knees suffered from overcorrection of the mechanical axis and progression of arthrosis in the non-replaced compartment. In two patients, progression of arthritis occurred despite the mechanical axis passing through the replaced compartment, indicating that alignment is not the only factor in the progression of arthritis in the compartment unaffected at the time of surgery. It is possible that in lateral compartment osteoarthritis, early minimal degeneration of the opposite tibiofemoral compartment and patellofemoral compartment are of significance and not to be ignored. Although lateral unicompartmental knee replacements showed a survivorship of 97% at five years, it dropped to 41% at eight years. Seven patients in our series had fair results according to the Bristol knee score. They continued to have pain on activity and occasionally at rest. Four of these patients had progression of arthrosis in the non-replaced compartment. Two of the seven patients had overcorrection of the mechanical axis. The other five patients had satisfactory alignment, but three patients showed progression of arthrosis. None of these patients deemed their symptoms bad enough to consider conversion to total knee replacement.

It is possible that our method of assessment, of contra lateral and patellofemoral compartments regarding suitability for unicompartmental knee replacements, was flawed in some of these patients, which might explain the progression of arthrosis in spite of optimal alignment.

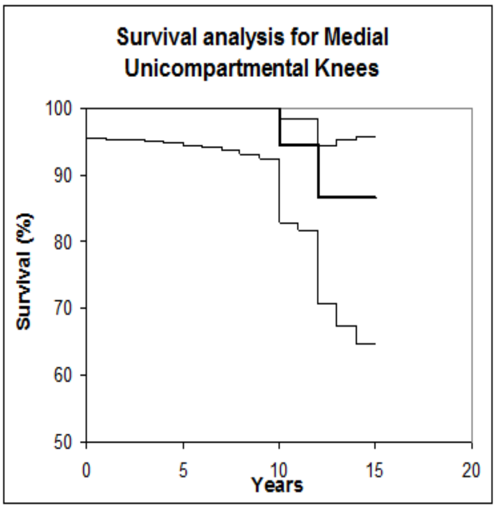


Figure 3.5 KM curve for Medial uni

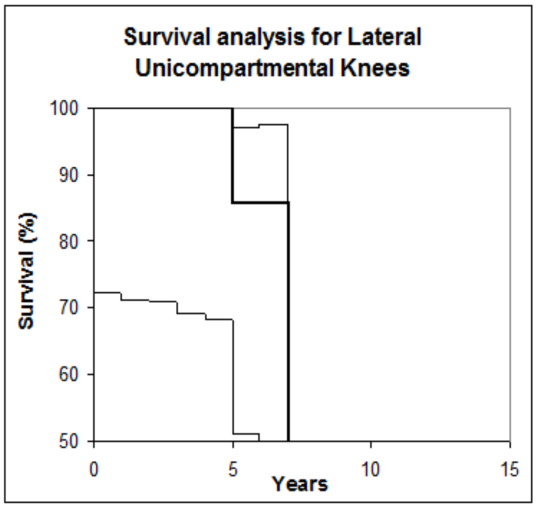


Figure 3.6 KM curve for Lateral uni

3.4.3 Discussion

The Miller-Galante unicompartmental prosthesis is a fixed bearing design. Although both metal-backed and all polyethylene tibial components are available, all patients in our series had a metal-backed tibial component. The results of this series suggest that this implant can provide excellent relief from pain, restoration of function and durable implant survival at 17 years follow-up, especially for medial compartment osteoarthrosis.

The mean age in our series was 66.54 years. Unicompartmental knee replacement is recommended in patients over 65 years by other authors (Squire 1999). Although unicompartmental knee replacements in the presence of early radiographic patellofemoral arthritis has been a contentious issue (Naudie 2004), none of the patients in our series required revision for progression of patellofemoral arthritis. This supports our use of clinical assessment and assessment at surgery, rather than radiological changes alone, as the rationale for single compartment resurfacing. The youngest patient at the time of surgery was 48 years old. Although knee replacement surgery at that age is debatable, as tibial osteotomy may be an equally attractive option, the excellent long term results achieved in that patient at 14 years follow – up, justifies the choice. Good survivorship and excellent outcomes have been reported in younger patients treated with unicompartmental knee replacements (Schai 1998, Engh 1999, Pennington 2003). These authors reported up to 92% eleven year survivorship, unlimited walking and participation in recreational sport in patients under 60. In spite of the excellent results achieved with unicompartmental knee replacements in younger patients, the opinion amongst surgeons is divided, as osteotomy allows the patient to keep their native joint with good outcomes.

There has been a recent trend towards minimally invasive implantation of medial unicompartmental knee replacements, in the hope of decreasing soft-tissue trauma and dissection. The proponents of minimal invasive surgery believe that this approach expedites recovery and achieves earlier return to activity. The quicker rehabilitation is attributed to reduced soft tissue injury from not everting the patella such that rehabilitation is twice as quick when compared to traditional unicompartmental knee replacement (Price 2009). The quicker rehabilitation following unicompartmental knee replacement is thought to translate into 50% reduction of cost of unicompartmental knee replacements (Repicci 1999).

The analysis of alignment following minimally invasive unicompartmental knee replacement in large series has been reported to show risk of varus implantation. The larger standard deviation in the minimally invasive group also showed that minimally invasive implantation is not as reproducible as the standard technique (Fisher 2009). The implications of this finding for the long-term results of the procedure with contemporary implants are unknown. Although the clinical results of the minimally invasive approach are comparable to the traditional open approach, caution has been emphasised by authors especially during the surgeon's learning curve (Luscombe 2007). All the patients in this series had the prosthesis implanted via an open approach as visual inspection of the tibio femoral compartments (both medial and lateral) and the patellofemoral joints was a critical part of the assessment of suitability for medial unicompartmental knee replacement.

None of the patients who received a unicompartmental knee replacement was anterior cruciate ligament (ACL) deficient. There is a general acceptance amongst surgeons that cruciate ligament deficiency is considered to be a contraindication for unicompartmental knee replacements (Koznin 1989). In the presence of anterior cruciate ligament, the pattern of arthritis is specifically anteromedial, which means that in weight bearing extension the knee is in varus due to loss of cartilage. But the intact cartilage in the posteromedial joint, keeps the medial collateral ligament to its normal length as the femur rolls back in flexion (White 1991). It follows that the anterior cruciate ligament protects the degeneration of the posteromedial and lateral compartment cartilage and prevents development of fixed varus deformity (White 1991).This means that as the knee does not develop fixed varus, the medial collateral ligament does not contract and does not need to be released at the time of surgery. Moreover significant tibial translation of up to one centimetre has been reported in cadaveric models at a wide range of knee flexion angles in the setting of anterior cruciate ligament insufficiency which could lead to instability and early wear following unicompartmental knee replacement (Suggs 2004). This has been borne out by the results of unicompartmental knee replacements in anterior cruciate ligament deficient knees where the survivorship was 81% compared to 95% in knees with intact ligament (Goodfellow 1992).

The rate of survival of implants in medial unicompartmental knee replacements is comparable to other reports of both fixed and mobile bearing designs (MacKinnon 1988, Scott 1991, Heck 1993, Ansari 1997, Murray 1998, Berger 1999, Squire 1999, Newman 2001, Perkins 2002, Argensen 2002, Rajasekar 2004). A study with large number of patients have reported higher revision rates for medial unicompartmental knee replacements, but once technical errors and surgeon-related complications were discounted good survival rates were reported (Collier 2006, Mercier 2009). Although the survival rates of lateral unicompartmental knee replacements in large series have been reported to be lower than medial unicompartmental knee replacements (Ashraf 2002), the survival rate of lateral unicompartmental knees in our series beyond five years was disappointing. The majority of revisions were due to progression of arthrosis in the unaffected compartment. Although the number of patients (nine patients) who had lateral unicompartmental knee replacements is too small to make significant inferences about survival rates in this group of patients, we believe lateral unicompartmental knee replacements behave differently from medial unicompartmental knee replacements. A recent report with a very high rate of survival in lateral unicompartmental knee replacements has recommended placing the tibial base plate in internal rotation to counter the effects of the 'screw home' phenomenon (Pennington 2006). Symptomatic unicompartmental knee replacement is treated with conversion to total knee arthroplasty. As technical and implant-related factors have improved, the challenges of such revisions have gradually decreased. In 1991, following conversion of twenty one knees of which sixteen had a major osseous defect, the authors concluded that revision of a unicompartmental knee replacement to a total knee replacement provides no advantages regarding technical ease or bone loss compared with a standard revision knee replacement (Padgett 1991). Subsequent series reported a significant requirement of cancellous bone grafting, metal wedges and requirement for structural bony allografts (Levine 1996, Saragaglia 2009, Jarvenpaa 2009). Large series have countered this view with only 22% requiring prosthetic augments and stems, and 78% of the conversions managed with standard total knee replacement prostheses (Chakrabarty 1998). In our experience neither removal of cement nor loss of bone stock was a significant problem at the time of surgery. The functional results of unicompartmental knee replacements converted to total knee replacements have been found to be worse than primary knee replacements (Jaarvenpa 2009), but the improved kinematics (Manzotti 2007) and consistently better knee scores (Newman 2001) in successful medial unicompartmental knee replacements justify their use over total knee replacements in appropriate patients.

There are two versions of the Bristol knee score. The hundred point scale is the one that is commonly used now. The scoring system used in this study was the fifty point score. The 50 point score was found to be most reliable in comparison with other knee scores. The 50 point Bristol knee score when compared to the Hungerford, Hospital for Special Surgery and Knee Society scores was reported to have excellent interobserver reliability (Bach 2002).The use of Bristol knee scores in the assessment of unicompartmental knee replacements has not been validated, although it has been used by previous investigators (MacKinnon 1988). The discrepancies between the total score and the function score would account for variations in patients due to comorbidities even in the presence of good knee function. Most authors, reporting on the results of Miller-Galante unicompartmental knee replacements, have used other scoring systems, which makes direct comparison of function between cohorts difficult. This is a limitation of this study.

3.4.4 Conclusions

The results for medial unicompartmental knee replacements are similar to reports by other authors for fixed and mobile bearing designs. Medial unicompartmental knee replacement results in good function with very good survival rates at 17 years. Conversions to total knee replacements, when necessary, have not been technically difficult procedures.

The elimination of pain and improvement of function in the knee following medial unicompartmental knee replacement indicate that this surgical model is adequate for the purpose of investigation of loading of the medial compartment of the knee.

3.6 Report II

This report details the effect of alignment on function scores following unicompartmental knee replacements as part of study 1. It analyses the efficacy of the location of mechanical axis on the tibial plateau over the tibiofemoral angle for the purpose. So a separate relevant introduction briefly reviews the literature on use of the two parameters and importance of alignment.

3.6.1 Introduction

Unicompartmental knee replacement arthroplasty (UKA) has been an option for the treatment of osteoarthritis of a single compartment in the knee for many years. Although Unicompartmental Knee replacements have demonstrated good survivorship at 10 years after implantation, most authors recommend careful selection of patients. Factors such as age, weight, level of activity, accurate diagnosis and alignment influence the outcome (Bert 1997, Marmor 1998, Ridgeway 2002, Stern 1993). The correction of alignment achieved at surgery after careful assessment of the preoperative deformity is the single most important factor that can be controlled by the surgeon during replacement surgery of the knee (Moreland 1988). The correct postoperative limb alignment to be achieved after UKA is uncertain (Keene 2006). The knee in the normal population is in slight varus alignment (Kraus 2005), and this justifies the traditional belief that undercorrection should be recommended to restore the physiological alignment for the individual knee and prevent accelerated wear of the normal compartment (Scott 1991). Accelerated wear of the non- arthritic compartment and poor results have been reported after overcorrection of alignment (Kennedy 1987). Similarly severe under correction with residual varus alignment leads to accelerated wear of the prosthesis (Barrett 1987). The influence of alignment on the outcome has led some authors to recommend that the alignment should be restored such that the mechanical axis passes through the centre of the knee following total knee replacement (Emerson 2002). The tibiofemoral angle (between anatomical axes) is variable and ranges from 167.5° (varus) to 195.5° (valgus) in the normal population (Kraus 2005). A 5 to 10° valgus correction of the tibiofemoral angle (between anatomical axes) relative to the initial alignment has been reported to correlate positively with survival (Stern 1993). However, restoring alignment to achieve a particular correction of tibiofemoral angle may not necessarily restore the mechanical axis to the centre of the knee. If the alignment needs to be such that the mechanical axis passes through the centre, then tibiofemoral angle corrections for individual knees have to be calculated individually in order to restore knee alignment optimally. The aim of this analysis was therefore to answer two questions:

(1) Do tibio femoral angle (between anatomical axes) and location of the mechanical axis in the knee correlate?

(2) Does the location of the mechanical axis influence the function of the knee?

3.6.2 Radiological analysis

The location in the knee through which the mechanical axis passed was assessed from the long leg views. We used a modification of the method described by Kennedy and White (1987), to assess the zone through which the mechanical axis passed (Figure 3.7). The proximal tibial articular surface was divided into zones: 0 (central or area of tibial spines), 1 (inner half of the medial or lateral tibial plateau), 2 (outer half of the medial or lateral tibial plateau), 3 (outside the tibial plateau) (Figure 3.8). Over - correction was represented by negative values of the above mentioned numbers. The tibiofemoral angle was measured as the angle between two lines representing the tibial and femoral anatomical axes. The tibial axis was represented by a line joining the centre of the tibial spines to the centre of the talus. The femoral axis was represented by a line joining the mid points between the outer cortices of the femur at the isthmus and ten centimetres proximal to the knee joint line. Valgus alignment was represented by positive values while varus angles were represented as negative values in degrees.

Figure 3.7 Tibial zones (Kennedy 1987) **Figure 3.8 Tibial zones (John 2009)**

The modification of the nomenclature of tibial zones was done to appropriately represent the negative effect of overcorrection.

3.6.3 Statistical analysis

To check whether tibiofemoral angle and location of mechanical axis measure the same, single regression analysis was used. Single regression analysis was also used to assess the relation of age, duration of follow-up and alignment based on the mechanical axis or the tibiofemoral angle (between anatomical axes) to function. Multiple regression analysis was used to assess the relation between alignment and function, corrected for age and follow-up. The regression analyses of function with alignment were based on the square of the tibiofemoral angle and the mechanical axis zone. This was done because the plot of Bristol knee score to alignment measures showed a curvilinear rather than a linear spread suggesting a quadratic rather than a linear relationship.

A p value less than 0.05 was assumed to denote statistical significance. All statistical analyses were performed using SYSTAT vs. 11 (Systat Software Inc, Point Richmond, USA).

3.6.4 Results

The mean follow-up was 10.8 years (range 2 to 16 yrs). The mean age at follow-up was 71.3 years (range 56 to 81y, SD= 7.12y). The mean total Bristol knee score at follow-up was 43.6 (range 28 to 50, SD= 6.44). The mean functional score was 16.3 (range 9 to 20, SD= 3.86). A total of 86% of the patients had a good or excellent total score. In six knees (two lateral and four medial unicompartmental knee replacements), the mechanical axis passed through the non-replaced compartment, due to inadvertent over - correction. In 48 knees (88%) undercorrection was achieved, i.e. the mechanical axis passed through the central zone or inner half of the medial tibial plateau in medial unicompartmental knee replacements and the central zone or inner half of the lateral tibial plateau in lateral unicompartmental knee replacements. In five of these knees, the mechanical axis passed outside the tibial plateau itself (zone 3) suggesting severe undercorrection. The average tibiofemoral angle (between anatomical axes) ranged from 15.5° valgus to 11.1° varus (mean: 1.11° varus ± 9.2°SD). In patients who had good or excellent function, the tibiofemoral angle (between anatomical axes) ranged from 15.5° of valgus to 8.4° of varus (mean : 2.65° varus ± 5.4°SD). When only the knees with the mechanical axis passing through the central zone was analysed, it was found that the average tibiofemoral angle ranged from 11.1° valgus to 7.3° varus (mean : 3.28° valgus ± 6.8° SD). There was a moderate correlation between tibiofemoral angle and location of mechanical axis ($r = 0.54$, $p < 0.01$). Of the four single factors analysed (duration of follow-up, age and alignment defined by mechanical axis or tibiofemoral angle (between anatomical axes), only age of the patient and location of mechanical axis significantly predicted the knee score (table I). We did not find a significant relationship between tibiofemoral angle or duration of follow-up and function.

Table 3.1 Factors affecting Bristol knee Score

Factor	Partial correlation coefficient (R^2)	p value
Age at FU	0.26	< 0.001
Period of FU	0.00	0.92
Mechanical axis	0.22	0.001
Tibiofemoral angle	0.08	0.11

Using multiple regression analysis to correct for the effect of age on score, a significant relationship was found between the location of mechanical axis and function ($p < 0.003$; table II).

Table 3.2 Correlation coefficient of the two alignment variables assessed

Factor	Partial correlation coefficient (R^2)	p value
Mechanical axis	0.39	0.003
Tibiofemoral angle	0.06	0.12

The Bristol knee score was maximal when the mechanical axis passed through zones 0 or 1. The average functional score of those patients was 18% higher than in patients in whom the mechanical axis passed through the other zones (45.8 ± 4.8 vs 38.8 ± 7.0SD, $p < 0.01$, t-test). The relation between mechanical alignment and function (Bristol knee score) was not a linear relation but a quadratic relation.

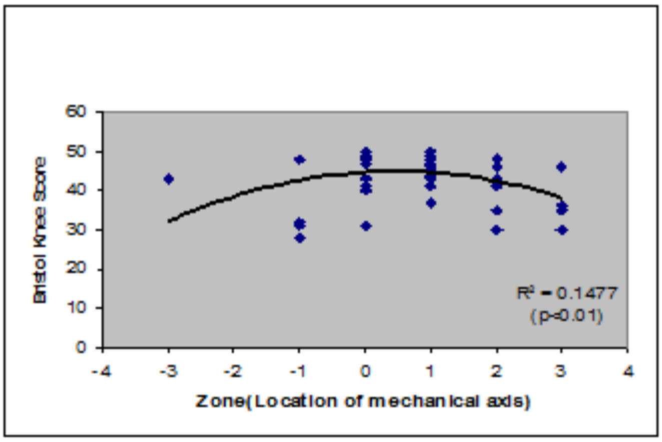


Figure 3.9 Quadratic relationship between BKS and location of MA (Fig.3.8).

3.6.6 Discussion

The aim of this study was to determine whether the location of the mechanical axis influences function after unicompartmental knee replacement. The knees in which the mechanical axis was located centrally in the operated compartment had significantly better Bristol knee scores. The location of the mechanical axis appeared to be a predictor of knee function even after the score was corrected for age. Our results show moderate correlation between the two measures of alignment, namely the tibiofemoral angle measured between anatomical axes and the location of mechanical axis at the knee joint. Since the range of acceptable tibiofemoral angles for those knees where the mechanical axis passes through zones 0 or 1 would fall within a limited range, some correlation is to be expected.

Although it is well accepted that alignment influences survivorship, most authors have not found any correlation between function and alignment (Stockelman 1991, Kennedy 1987, Collier 2006). Our finding of correlation between alignment and function seems to contradict the findings in another study investigating this effect on function (Stockelman1991). In that study, no correlation was found between Hospital for Special Surgery scores and alignment, including tibiofemoral angle and location of mechanical axis. However, in our study the relation between mechanical alignment and function was not a linear relation but a quadratic relation. This relation reflects the fact that the Bristol Knee score is maximal when the knee is aligned with the mechanical axis passing through the centre of the knee (zone 0) or through zone 1, and is smaller when the knee is under or overcorrected. The analysis done in the report by Stockelman et al (1991) using Pearson's correlation coefficient attempts to identify a linear relationship between variables. This would show as a line on a plot. If the relationship is curvilinear, Pearson's coefficient would fail to establish an effect of optimal alignment. In our study the relationship is established between the squares of the values of alignment and location of mechanical axis (Quadratic relation). The scoring systems used in the investigation can have a significant impact as well. The Hospital for Special Surgery (HSS) scores have deductions for deviations from neutral alignment, as this was to assess total knee replacements, where neutral alignment of prosthesis is the surgical aim. When used in the scenario of unicompartmental knee replacements, where often neutral alignment is not the aim at surgery, it can clearly be inappropriate as the score will penalise knees in native alignment (Ridgeway 2004). The Bristol knee score has not been specifically validated for use in unicompartmental knee replacements, but the fact that it does not appear to penalise the score for mal-alignment, might have been a significant factor in our investigation revealing a positive relationship. Gulati (2009) have reported that function following unicompartmental knee replacements has not correlated with alignment. They found that the knees in varus seemed to have better oxford knee scores. In this study the alignment was not measured on long leg alignment radiographs but clinically using a goniometer. Although the measurement would be a valid assessment of alignment, whether findings on radiographic and goniometric data can be used interchangeably is debatable. The Oxford Knee Score does not have deductions for mal-alignment. The authors postulated that alignment should be such that soft tissue tension should be maintained.

Although this study found a moderate correlation between location of the mechanical axis and tibiofemoral angle (between anatomical axes) we do not believe that tibiofemoral angle is useful as a substitute for the location of the mechanical axis. In our study, patients who had a knee with the mechanical axis passing through the central zone had a large spread of tibiofemoral angles or anatomical axes (range 11.1° valgus to 7.3° varus, mean: 3.28° valgus ± 6.8° SD). This group included one patient who had a hip replacement and a fixation of a periprosthetic fracture that has left the mechanical axis of the limb passing through the center of the knee but the tibiofemoral angle (between anatomical axes) at 7.3° varus. If this patient was disregarded the tibiofemoral angle (between anatomical axes) measured showed a mean of 5.7° valgus. The large spread of tibio -femoral angles (between anatomical axes) in knees where the mechanical axis passes through the centre, can to some extent be attributed to variations in gender and height of individual patients. With such a large spread, defining a specific range for the final tibiofemoral angle (between anatomical axes) to ensure that the mechanical axis passes centrally is difficult. Moreover in order to ensure central alignment of individual knees the correction of mechanical axis needs to be calculated for each knee. Although tibiofemoral angle may be useful as a measure to calculate correction of alignment following surgery, its use in assessing the effect of alignment on final function may not be ideal.

The location of the mechanical axis was not the best predictor of function. Age at follow-up proved to be a better predictor, with patients having poorer scores with increasing age. There was no significant correlation of function with duration of follow- up. In other words, patients who had an implant for a longer period of time did not necessarily have a worse score. The combination of the two findings suggests that worsening of the score with age was due to worsening of the general condition with age, rather than worsening of the condition of the implant with time. Although age had a relatively large effect on function, location of the mechanical axis was still a significant predictor after correction for age.

The use of Bristol knee scores in the assessment of unicompartmental knee replacements has not been validated, although it has been used by previous investigators (MacKinnon 1987). Bristol knee score when compared to Hungerford, Hospital for Special Surgery and Knee Society scores has been reported to have excellent intra and inter observer reliability (Bach 2003), although for this study all the scores were recorded by a single investigator. The Bristol knee score has a functional component as part of the total knee score. The discrepancies between the total score and the function score would account for variations in patients due to co morbidities even in the presence of good knee function. The effect of co morbidities on function was borne out by the fact that age had a very significant relationship with function even though duration after surgery did not.

Although this study is a single surgeon consecutive series where the same technique and implant has been used in all patients, it has the weaknesses of a retrospective study. Moreover we did not have sequential radiographs for all the patients analysed. We could not monitor and analyse the loss of the correction of alignment achieved at the time of surgery over a period of time, which has been reported previously (Ridgeway 2004). Although preoperative alignment views were obtained, they were not used to calculate the correction necessary at surgery to have the mechanical axis pass through the centre. All the pre operative alignment radiographs were not available to assess the surgical correction achieved even if inadvertently, as there was no attempt to realign the knees presented in this series to have the mechanical axis pass through the centre of the knee. The finding that knees which were more neutrally aligned had better knee function scores, might be due to the fact that these knees originally were in neutral alignment prior to surgery, as the surgeon set out to leave the knee under corrected than achieve neutral alignment. The more varus alignment in knees has been considered as a significant factor in progression of medial unicompartmental osteoarthritis and this is known to be related to the loads that pass through the knee (Sharma 1998). That neutral alignment leads to less of a risk for progression of osteoarthritis and better function scores in native knees might have an effect following replacements as well due to factors like soft tissue tension. However, in the light of the findings in this series, we believe that optimum alignment is ideal and there is a definite case that this should be attempted in unicompartmental knee replacement arthroplasties as long as it is not at the expense of ligament balance.

3.6.7 Conclusion

In conclusion, age at follow-up and location of the mechanical axis are good predictors of function after unicompartmental knee replacement. The mechanical axis should pass through the tibial spines or just on the inner half of the replaced compartment. Such an alignment improved Bristol Knee score by approximately 20%.

This investigation has revealed that alignment of the knee following unicompartmental knee replacements significantly affected function.

Chapter 4

Gait Analysis

This chapter outlines the history, methodologies and parameters assessed as part of gait analysis. Joint moments assessed as part of gait analysis was used to assess loading of the medial compartment of the knee. The chapter also discusses the evolution of various technologies used, especially the one used for this investigation. The relevance of individual paramaters in the assessment of gait in osteoarthritis of the knee and following replacement arthroplasty are described. The literature on parameters of gait affected by osteoarthritis and replacement arthroplasty is discussed in detail. This chapter is intended to reflect the evolution of understanding of gait analysis, considering the surgical back ground of the author, as a result detailed discussions on the mathematical basis and technological details are avoided.

4.1 Brief History of Gait Analysis

The history of gait analysis is commonly divided into two halves by the introduction of computerisation, which marked a paradigm shift in management and analysis of data at high speeds (Baker 2007). The ancient Greeks were interested in gait of humans and descriptions of it have been recorded in the works of Aristotle. Although the patterns of gait have interested anatomists for long, it is only in the last 150 years that these ideas have been put into use and developed further to be used in a reliable and repeatable manner (Kirtley 2006). The progress in the understanding of gait has paralleled the advances in science and technology. In his work 'De Motu Animalum'(On the motion of animals), the renaissance scientist Giovanni Borelli described the parallels he found between gait and the machinery of his day (Baker 2007). In clinical medicine the description of gait by James Parkinson in patients suffering from Parkinson's disease and that by Friedrich Trendelenberg in paralysis of the abductors around the hip have become eponymous. Most work on gait till the late nineteenth century tended to be observational and descriptive. The invention of the photographic technique by Niépce in 1822 was revolutionary, as it made it possible to record an incident without sketching or painting it. After Niépce's sudden death in 1833, his co-worker Louis Daguerre continued the work and made further developments. At the early stage of the photographic era, the exposure time was extremely long, making it impossible to capture motion, so photographs from this time were only taken of static objects, such as landscapes. Work on the further development of the photographic technique led to reduced exposure time, which made it possible to capture the movement of both animals and humans (Baker 2007). Eadweard Muybridge, an English photographer in 1872 developed the technology to record the gait of horses and prove that while trotting at full speed (30m/s) there are occasions where all four limbs are off the ground (Muybridge 1878.). This was a forerunner to the development of cinematograph by the Lumiere brothers in Lyon. The earliest work on three-dimensional gait analysis in human beings was done by Fischer and Braune. They recorded the human movement of a German infantry soldier in the summer of 1891(Braune 1889). The advent of motion picture technologies dramatically improved the method of capturing dynamic events. Movie cameras were used throughout the 1960s and television imaging cameras were introduced (Winter 2005).

The Vanguard motion analyser used film based techniques on passive marker systems. It used high speed cameras to track markers in space, but conversion to coordinate data was done manually. This was a time consuming process. The next advancement came with the Vicon system, name of which came from 'Video- converter'. This was marketed by the Oxford Orthopaedic Engineering Centre (Vicon Ltd, U.K.). The 1980s saw the Oxford Orthopaedic Engineering Centre produce the Vicon motion capture system (Vicon Ltd, U.K.). Micheal Whittle who was working with the NASA on the skylab project, became the director of the Oxford University Motion Laboratory. Whittle is believed to have written the 3D motion capture software for Vicon, leading it to become one of the most commonly used gait analysis systems in the United Kingdom. After the Oxford Metrics, Motion Analysis Corporation was the next big company to emerge in the motion capture market (Sutherland 2002). The Bioengineering Technology Systems (BTS Milan) was set up during 1980s. The ELITE system was developed and is used extensively in centres in Europe for motion capture applications like clinical gait analysis (Ferrigno 1985). In the recent decades, interest has primarily focused on higher resolution cameras and higher frequency of recording, which have made it possible to record rapid movements and use markers with smaller dimensions, especially in motion analysis of very small joints.

Instrumented gait analysis records both movements or kinematic studies and analysis of forces or kinetics. The recording of the forces through joints is done with the use of force plates which could record three dimensional force components during gait. The early development of force plate, can originally be attributed to Jules Amar who used a pneumatic technique to record forces in the early part of the twentieth century. A mechanical version of a three-dimensional force plate was described in 1938 by Elftman (Elftman 1938). In the mid part of the last century development was largely on research-based gait analysis, due to problems of reliability, affordability and longevity. The earliest commercially available gait analysis system was a piezoelectric force plate, developed by Kistler (Kistler Group, Switzerland) for use in a laboratory. The force plates used in gait analysis today are usually electronically operated devices using strain gauges like the AMTI platform or piezoelectric technology, like the Kistler platform, with either technology offering different advantages depending on the circumstance of use. Motion capture cameras and force plates are now well established technologies used in gait analysis by researchers in a variety of locomotor problems in human beings, the gaming industry and by veterinary scientists especially in the study of equine locomotion (Baker 2007).

4.2 Gait analysis in joint replacement surgery

The use of gait analysis for measurement of outcomes following joint replacement surgery especially total knee replacements have increased and led to improvements in design and surgical technique (Fransen 1997, Hilding 1996, Hilding 1999). Gait analysis has been of great value in assessing kinetic and kinematic parameters which may be surrogate markers for long term function and survivorship following total knee replacement. Patients who have had clinically successful total knee replacement operations do not necessarily achieve successful long term function and survivorship of the knee joint. Gait abnormalities have been demonstrated even in patients with excellent clinical scores (Benedetti 2003). Gait analysis studies have used parameters very different from clinical outcome parameters. Reports of these parameters in literature tend to compare gait following total knee replacements to gait in normal patients. There appears to be a general view that normalisation of gait parameters is preferable and should be the goal of total joint replacement surgery. This is based on the assumption that restoration of normal gait patterns is beneficial in achieving better function and long term survivorship, even though the material properties of articulating surfaces in native knees and replaced knees are very different. Although this would seem to be intuitive, it is not backed up with sufficient evidence. Even though the effect of restoration of normal gait parameters on long term survival of prosthetic replacements is uncertain, the restoration of normal gait parameters is very likely to be the result of soft tissue balance, which in turn leads to improved early and medium term results. Many authors have questioned the reliability of using these parameters to predict function and survivorship in the long term (McClelland. 2007). In the unicompartmental knee replacements, as the ligaments are kept intact without releases, the likelihood of achieving near normal kinetic and kinematic parameters is significantly greater (Patil 2006). It is generally thought that restoration of normal kinetic and kinematic profile should translate into better function following unicompartmental knee replacement arthroplasty as it restores appropriate soft tissue balance. Whether the restoration of near normal kinematics affects survivorship following unicompartmental knee replacement arthroplasty is not known. Unicompartmental knee replacements especially in the lateral compartment are known to have a lower survivorship as compared to medial unicompartmental knee replacements. The problems with dislocation of bearing in mobile bearing lateral unicompartmental knee replacements, has been attributed to excessive lateral condyle translation as compared to medial condyle (Robinson 2002). It is also thought that the different loading points in kinematically aligned lateral unicompartmental knees may be responsible for their lower survivorship (John 2006). So to assume that restoration of normal kinematics will be always beneficial in the long term may be misplaced. These uncertainties only emphasise the developing and sensitive nature of gait analysis in the field of joint replacements around the knee. But the loading patterns on the tibial component are of interest to scientists and clinicians, as inadequacies in this are likely to have a long term implication on the survivorship of the prosthesis.

Gait analysis allows the dynamic measurement of these loading patterns during gait. Gait analysis also allows the six degrees of freedom involved in movement of the knee joint during functional activities to be studied in dynamic mode. As a result, activities such as walking patterns following replacement arthroplasty have been examined closely (Banks 2003). Many different measurement systems have been used for gait analysis some of which are briefly reviewed below.

4.3 Gait analysis methods

The different methods used in analysis of gait can broadly be classified as kinetic methods that assess the loading across the joints and kinematic method that assess the range of movement.

4.3.1 Kinematic gait analysis

The methodologies used in kinematic gait analysis measures movement of the knee and specific phenomena like femoral roll- back.

4.3.1.1 Fluoroscopic systems

Fluoroscopic analysis uses x-ray analysis to examine bony structures of the knee dynamically. The images can be saved and can be produced at varying frequencies. Fluoroscopic systems have been used for the analysis of total knee replacement surgery, especially in studying the phenomenon of femoral rollback in different total knee replacement prosthetic designs (Steihl 1995). But the drawback of fluoroscopic systems is that it allows imaging only in a focussed area which makes it hard to assess the dynamic relationship between joints. As a result the use of these systems in circumstances such as treadmill analysis to assess walking whilst being video recorded can be restricted (Banks 1997). It also involves the drawback of exposure to radiation.

4.3.1.2 Triaxial goniometer systems

Triaxial goniometers were one of the easiest systems to be used for kinematic analysis of the knee joint (Stauffer 1977). This system consists of three goniometers that are linked with mechanical linkages to give a system that allows six degrees of movement. The system is placed across the lateral aspect of the knee joint to measure any movement patterns. This device was limited to a single joint. As the measurement system is direct and not subject to any mathematical modelling errors associated with the rotation of axis onto coordinate planes, it results in greater accuracy. Although the goniometric method is appealing, the large range of height and weight of the subjects resulting in difficulty in attaching them on to the body accurately. Also the difficulty encountered while walking with the large amount of hardware especially at higher speeds has limited the use of goniometers significantly.

4.3.2 Kinetic gait analysis

Kinetic gait analysis measures the forces across joints during gait.

4.3.2.1 Pressure mat systems

Pressure mat systems primarily measure the pressure distribution under the plantar aspect of the foot during activities. Some of these mats can accommodate bilateral foot falls and therefore can be used to record walking cadence and velocity, but has limited use in the context of investigations in the loading of individual joints.

4.3.2.2 Video vector systems

Video vector systems have the ability to produce fast and accurate information regarding the position of the resultant ground reaction force vector that passes through the Knee. A force plate mounted in the floor computes the vector and over lays this as a visual representation on to a video capture of the patient. Therefore, they are used to display the adduction moment of the knee. This system is useful in quick visualisation of the position of the resultant force vector as it passes through the knee joint. This is of great advantage when the effect of an intervention on the direction and position of the ground reaction vector is to be analysed in relation to the knee joint. The video vector systems have not been used a great deal in the analysis of total knee replacements.

4.4 Infrared video camera systems

Infrared video camera system measure both kinematic and kinetic parameters and resolves the forces through the different axes. Marker based infrared video camera systems is the most common choice of motion capture system that has been used in studies with participants who have undergone total joint replacement. A number of retro-reflective markers are placed on anatomical landmarks on the legs. Infrared sensitive closed circuit television cameras locate, and then record the movement of these markers when they are illuminated with infrared light. A sufficient number of cameras are positioned around the patient so that all of the markers are visible to the cameras during data collection procedures. As the patient walks along the walk way, if each marker is picked up by at least two cameras, then an absolute coordinate can be computed with reference to predefined global coordinate axis of the laboratory. Thus if three or more markers are placed on body segment in a non-collinear fashion, then a local coordinate system can be computed based on the assumption that the segment is rigid. Once the segment is defined, for example that of the femur and the tibia then related motion including rotations can be inferred from the local coordinate systems. This would allow for the calculation of joint angles in three planes (Woltring, 1994).

The retro reflective markers are placed on the skin as it is much more practical and noninvasive. As the reflective markers are attached directly to the skin, soft tissue artefacts are increased by muscle contraction and also the potential movement of these markers at the impact of the initial contact during the stance phase, can lead to the development of measurement errors when the joint angle and joint moment are calculated (Schwartz 2004). In order to make these measurements more reliable, and authentically measure motion that occurs between two body segments, invasive methods have been tried. Intra cortical pins have been used during the last two decades (Lundberg 1996, Manal 2002, Ramsey 2003). This method is still the most accurate way to obtain motion between two, or several, bony segments as it completely eliminates marker motion on the skin. Briefly described, bone pins are inserted into the bone under anaesthesia. Clusters of markers are then attached to the intra cortical pins in order to be traced with the optical tracking system. This method is, however, associated with limitations due to the risk of infection and ethical considerations and should most probably only be considered for use as an evaluation or validation method.

4.4.1 Skin Marker set

As clarified previously, skin mounted markers are more practical and for that reason most commonly used. A marker model is a set of spherical retro-reflective markers that make it possible to trace one or more body segments. Marker models are either based solely on a set of skin markers, so-called skin-based marker sets (SMS), or on a combination of skin markers and clusters consisting of a plastic shell and at least three markers attached to the shell. Skin markers are generally attached to the skin by double-adhesive tape, in contrast to clusters that are usually fastened with an elastic strap. Whether a skin marker-based model or a cluster-based model should be used is one of the fundamental questions that gait laboratories have to deal with, in addition to many other questions, during their start-up period. In practice what this means is that once a method is chosen by the laboratory they learn to use it within the envelope of advantages and disadvantages the system offers. From a clinical point of view, the Skin Marker Set (SMS) model is popular as it is easy to use. The application of markers is strictly based on well-known bony landmarks and has been extensively studied and reported in literature. The body is modelled as made up of rigid-body segments. Calculations of movements or forces (moments) at joints are based on the assumptions that all body segments can be considered as rigid bodies. Skin-markers are used for defining locations on body segments and to track body segments as they are moved. Comparisons between several marker models have been published. When five different protocols including skin markers, markers on wand and clusters were compared it was concluded that all five protocols showed good intra-protocol repeatability (Ferrari 2008).

Gait laboratories that assess neurological patients, focus on capturing sagittal and transverse parameters to assess flexion- extension and rotations, while gait analysis in osteoarthritis literature has largely been on coronal plane kinetics and kinematics (Davies. 1981). Roy Davis developed a marker set which was originally derived from his work and has been adopted by many leading motion analysis companies, albeit with modifications (Figure 4.1).

Anterior **Posterior** **Calibration marker removed**

Figure 4.1 Reflective markers as per Davis protocol (1981)

The axis measurements assume that each segment is a rigid body which in turn is defined by the skin markers placed on the anatomical landmarks. The axes are fixed in each body segment and move with it. Three or more markers are placed on each body segment from which a local co-ordinate system is calculated using the Gramm-Schmitt method of orthogonalisation. The first two markers define the primary axis, which is normally the main axis of the computation, and the third marker defines the relative rotation. The coordinates of bony landmarks are used to build a right-handed orthogonal coordinate system. The unique specification of anatomical coordinate systems requires a minimum of three non collinear points that are defined with respect to surface landmarks associated with each segment. In order to obtain the joint movement, expressions have to be obtained relating the position of each segment in the model with respect to adjacent segments. Joint motions are usually three dimensional. The anatomical description of the relative orientation of the two limb segments can be conveniently obtained by relating the two coordinate systems embedded in the proximal and distal body segments. By selecting and defining the axes of rotation between two bony segments, it is possible to make the finite rotation sequence independent. The concept of Euler angles has been adopted in the field of biomechanics to unify the definition of finite spatial rotation. The centre of the knee joint is computed by taking the position of the lateral knee marker, and offsetting by a distance that is half the measured width of the knee joint in the direction specified by the femoral thigh marker (Grood 1983). In general the proximal segment is chosen as stationary segment and the distal segment as the moving segment. For angles in the knee, the thigh segment is chosen as stationary segment and the shank as the moving segment. Given the joint positions, velocities, and accelerations, and the ground reaction forces, the joint moments can be calculated by an inverse dynamics approach proceeding from known kinematic data and external forces and moments to arrive at expressions of the resultant inter segmental forces and moments. An unconstrained rigid body has six degrees of freedom, which means six equations of motion are needed to specify its configuration.

Estimates of the mass of the body segment, centre of mass, and moments of inertia are needed for these biomechanical models. These body segment parameters are used along with the segmental kinematics to compute the linear and angular momentum of the body segments. Estimates of these values are substituted into the Newton-Euler equations of motion to obtain an estimate of joint loads during physical activity.

Calculation of quantitative values of joint moments is resolved with inverse dynamics. A fuller description of Euler angles and a more detailed description of inverse dynamics can be found in textbooks, for example, *Biomechanics and Motor Control of Human Movement* by Winter and *Clinical Gait Analysis Theory and Practice* by Kirtley.

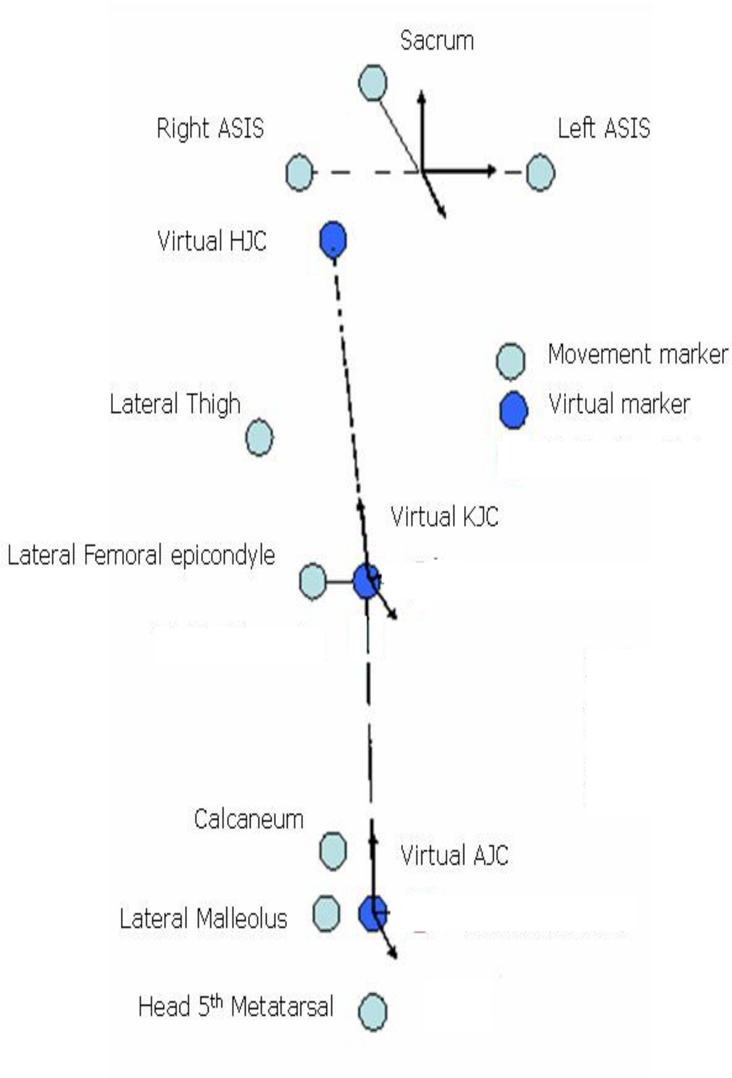


Figure 4.2.Markers representing the locations for the analysis of the right knee. (*They are transposed for representation of the left knee)*

Failure to place markers accurately is probably the single greatest contributor to measurement variability in contemporary clinical gait analysis. This can be attributed to the fact that many of the landmarks used to guide marker placement not being particularly well defined in many patients. Although correct placement of the skin markers can be achieved by training the personnel involved, difficulty in locating the landmarks precisely for appropriate marker placement can be significant (Della Croce 2005).

In order to avoid the errors secondary to inaccurate marker placement, methods have been designed for moving away from the accurate identification of anatomical landmarks. This process is known as anatomical calibration and has been around for some time (Cappozzo 1995). They rely on calibration movements to be performed before capturing walking data and some form of fitting of the measured marker positions to an underlying model. The difficulties in execution of the calibration movements by patients with significant pathologies have limited its widespread use.

The problem of skin and soft tissue movement artefact can be a significant problem. Attempts have been made to address this in different ways, like fitting a model to the marker coordinate data or by using direct measurement techniques like the use of Magnetic resonance imaging (MRI) and fluoroscopy. These methods are very restricted in their use as capture volumes tend to be limited (Leardini 2005).

Studies using motion analysis to evaluate improvements in clinical parameters with time following replacement arthroplasty have shown that recordings at 6, 12 and 24 months of the kinematic and kinetic parameters were consistent and does not improve significantly beyond 6 months (Benedetti 2003). For this reason measurements at 6 months can be taken to be permanent gait characteristics following surgery.

4.4.2 Assessment of intra-segmental motion

Use of roentgen stereo photogrammetric analysis (RSA) with the use of bony anchored tantalum balls is a method for detection of intra-segmental motion with high precision. The method was originally described by Selvik in 1974 (Selvik 1989). In the early period the technique could only be used in static mode, for example the investigation of subsidence of femoral stems following total hip arthroplasty. In 1988, Kärrholm and co-workers published the first study on knee kinematics in which they used a dynamic version of RSA (Kärrholm 1988). The dynamic RSA consists of two ceiling-mounted radiographic tubes with a common angle exposed at the same time on two film exchangers. This still involves the use of radiation which limits its use commercially where optical systems with skin markers have become very popular due to the distinct advantage of avoiding radiation. When using retro reflective markers, the ideal situation would be if these markers were attached directly to the bones concerned, but this would be impractical for repeated measurements due to its invasive nature (Lafortune 1992). Markers that have been surgically implanted at the time of prosthesis insertion, like patients with replacement arthroplasty have been used extensively in research around total hip and total knee replacements especially to assess migration of prosthesis.

4.5 Gait cycle

A gait cycle is defined as the sequence of events, which occurs from initial contact of one foot to the successive initial contact of the same foot. In healthy adults, 60% of the gait cycle is represented by stance phase (foot is in contact with the ground) and the remaining 40% of the cycle is represented by swing phase (when the foot is not in contact with the ground). Stance phase is divided into four sub-phases: loading response, mid-stance, terminal stance, and pre-swing. Swing phase is also sub-divided into early swing, mid-swing, and late-swing phases. In a gait cycle, there are two periods of double limb support (both feet contact the ground) and two periods of single limb support (body supported by a single limb) (Olney. 2005).

Gait Analysis tends to incorporate a broad spectrum of individual outcome measures. The different parameters include time, distance, kinematic and kinetic parameters. This thesis concentrates on the alterations in kinetic and kinematic parameters following unicompartmental knee replacements and the factors that affect the kinetics of the knee especially in the coronal plane.

4.6 Review of literature on gait analysis in unicompartmental replacements

A systematic review of literature was completed. The Medline® Database was searched using the combination of the following keywords: unicompartmental knee, unicondylar knee, gait, gait analysis. Any papers that contained these keywords in the title, keywords or the abstract were retrieved for analysis.

This narrowed the search down to 22 articles. Of these, one article was in German and another in Danish, these were eliminated for the purpose of the study. Of the remaining 20 articles, the abstracts were carefully reviewed, 3 articles reported kinematic assessment using fluoroscopy, 3 articles reported findings on Finite Element Modelling, one article was a review article which has since been retracted. There were six articles on clinical results following unicompartmental knee replacements and these have been referenced in a previous section. Seven articles had used parameters measured by instrumented gait analysis of which five articles restricted their observations to temporospatial parameters. Only two articles have reported results on kinetics or loading parameters in medial unicompartmental knee replacements as measured by instrumented gait analysis. These seven papers have been carefully reviewed and discussed in detail in the review of literature on gait analysis. The review of literature has been written as a narrative review as it is intended to include discussions on the efficacy and appropriateness of the various parameters of gait analysis used for the purposes of assessment of dynamic loading in unicompartmental knee replacement. This includes literature outside gait analysis in unicompartmental replacements. Although a description of kinetic and kinematic parameters as measured by instrumented gait analysis following medial unicompartmental knee replacement has been reported (Chassin 1996, Catani 2012), a measurement of the effect of surgery (i.e. correction of coronal alignment on dynamic loading parameters of the knee) is found to be lacking in the literature. Moreover the use of adduction impulse inspite of its advantage over peak moments have not been reported in the context of analysis of medial unicompartmental knee replacements.

4.7 Review of literature on Time and distance parameters

The percentage stance phase of the gait cycle is typically 60%. Stance duration is accepted as an indicator of stability, with instability decreasing the proportion of stance phase (Perry, 1992). Cadence is the number of steps taken per minute. Several authors have reported values for cadence with approximately 20% reduction in value in pathological cases (Benedetti, 2003). Although authors agree that pathology results in reduction in cadence, the values themselves tend to be variable. Reduction in stance phase, cadence and walking velocity have been reported following investigations in knees with osteoarthritis (Gok 2002) and also following total replacement surgery (Andriacchi 1982). Studies reporting gait parameters following unicompartmental knee replacements using instrumented gait analysis have reported improvement in gait speeds and cadence (Mattsson 1990, Fuchs 2003, Webster 2003, Borjesson 2005, Fuchs 2005, Borjesson 2007). Although electromyographic findings during gait on patients with unicompartmental knee replacements have questioned the return to patterns found in age matched inviduals (Fuchs 2005), there is consensus amongst authors that gait speeds and cadence improves significantly following unicompartmental knee replacements along with the improvements in energy consumption and quality of life in this geriatric population (Mattsson 1990, Fuchs 2003, Webster 2003, Borjesson 2005, Borjesson 2007).

4.8 Review of literature on kinematic analysis

Kinematics is a branch of biomechanics that is concerned with human movement without considering the forces that cause the motion. Kinematic gait variables include linear and angular displacements that describe the range of motion of a body segment in relation to an adjacent segment (Kirtley 2006).

For the purposes of biomechanical measurement, the knee joint is defined as the joint between fixed body segments of tibia and femur which are major long bones. During the stance phase of the gait cycle, the mass of the person is transmitted through the knee joint and during the swing phase the knee is generally flexed to allow for the advancement of the limb by allowing ground clearance. The motion of the knee is very complex. In the sagittal plane this motion is large ranging up to 60°-70° of flexion for free walking alone, and much greater for other activities as this is the plane of natural movement of the knee**.** The motion in the transverse and coronal planes is much smaller (maximum of 9°) in comparison.

The knee begins the gait cycle in a position of maximum internal rotation, from that point the whole lower limb including the pelvis, femur and tibia externally rotates through the stance phase. At final contact the knee begins to internally rotate and continues until initial contact of next step to reach a maximum during the loading response of early stance (Perry 1992). In the transverse plane it has been demonstrated that the average rotation of the knee during walking was 9°. In the coronal plane, the knee can undergo both adduction and abduction. During the loading response, the anatomical alignment of the knee is governed by the anatomical alignment of the tibia and femur under the influence of body weight. This motion is under the action of centripetal forces of the centre of mass of the lower limb, which tends to open the joint up but is prevented in doing so by the restraints of the soft tissues (ligaments and muscles). In the majority of the population, the knee tends to be aligned in adduction or varus. The ligaments are static restraints while muscles are dynamic and actively alter the moments by varying the power of contraction and alteration of synchronisation of contraction.

In the transverse plane, the external rotation of the knee joint (external rotation of the thigh segment with reference to a relative internal rotation of the tibial segment) is assessed in gait analyses studies. Although the transverse plane parameters are significant in neuromuscular gait and have been studied and reported in literature, they have not been analysed as much in detail in gait analysis literature of osteoarthritic knees as the coronal and sagittal plane gait parameters have been.

4.8.1 Sagittal plane kinematics

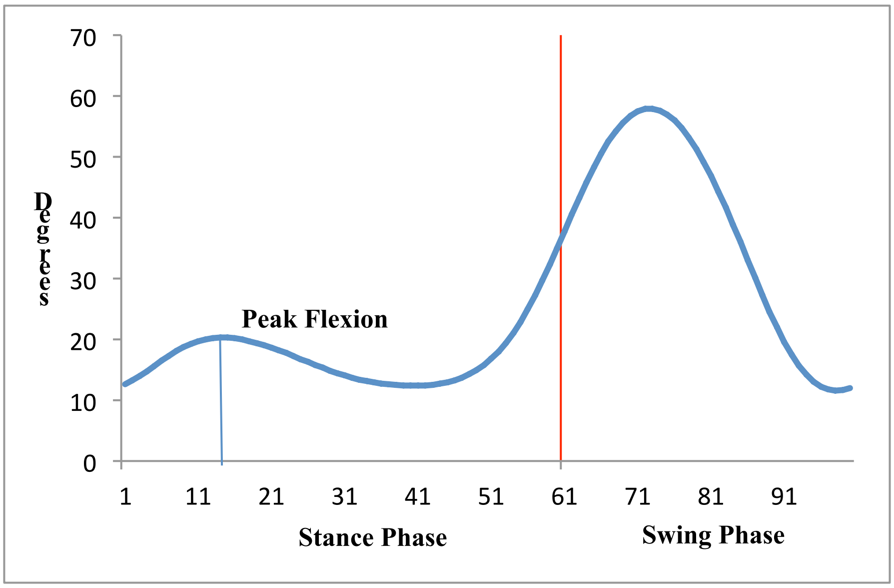


Figure 4.3 Flexion – Extension in Stance and Swing phase

The sagittal plane kinematic parameters include flexion and extension in stance and swing. Differences in sagittal plane knee joint kinematics in osteoarthritis of the knees compared to healthy controls during level-walking have been reported extensively in the literature (Kaufman 2001, Gok 2002, Mundermann 2005, Zeni 2009). The most consistent difference between osteoarthritic knees and normal knees in sagittal plane include smaller stance phase peak knee flexion (Al-Zahrani 2002, Gok 2002; McKean 2007) and smaller knee flexion range of motion in first half of stance phase (Zeni 2009). It follows that smaller peak knee flexion values lead to smaller knee flexion range of motion during stance. In a report on gait characteristics of the lower limb data was collected in fifty-four adults aged 50 years or older with medial compartment knee osteoarthritis during walking (Zeni 2009). These variables were then analysed to assess the effect of gait parameters on the clinical scores like Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) scores, especially the pain component in all participants. A smaller knee flexion was significantly correlated to higher pain scores in patients with osteoarthritis of the knee. The difficulty among authors has been whether the reduction in range of motion is secondary to the arthritis or a forerunner to it. A potential explanation for these higher pain scores with smaller range of movement of the knee may be that joint reaction forces are distributed less evenly across a smaller area of the tibial and femoral joint surfaces. These increased pressures in the focal areas of the knee joint surfaces result in continuous high loads which may explain greater cartilage and subchondral bone damage resulting in pain in patients with osteoarthritis of the knee. Smaller knee flexion angles have been linked to reductions in medial compartment femoral cartilage thickness (Koo 2011) which could indicate greater force application on the medial knee compartment. Although loading of the articular cartilage is necessary to maintain the thickness of the articular cartilage as shown by MRI scan assessments in joints on paralysed limbs (Vanwanseele 2002), the loading needs to remain within physiological parameters. The alteration in the surface area of the joint through which the loads pass result in pathological loading patterns with the consequence of osteoarthritis

4.8.2 Coronal plane kinematics

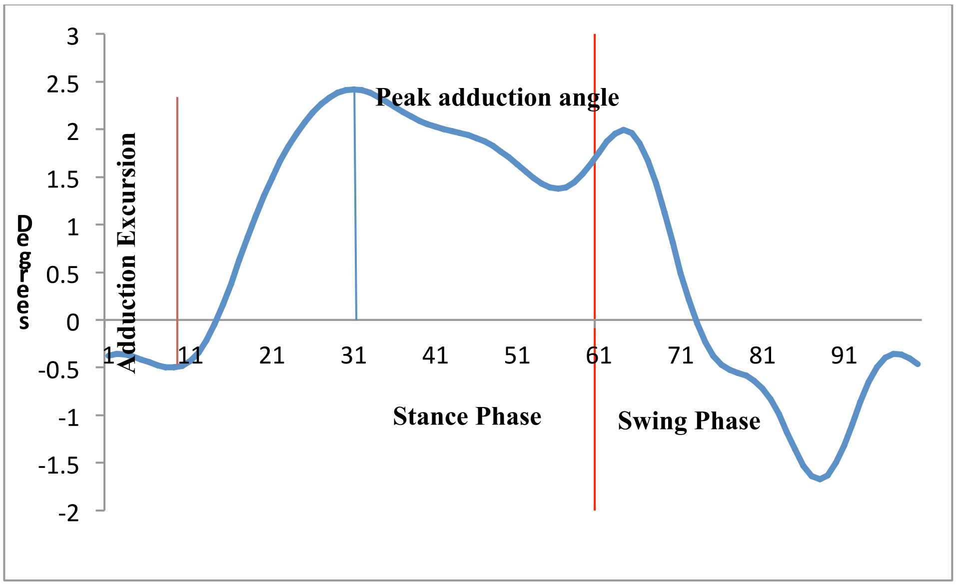


Figure 4.4 Varus (Adduction) Valgus (Abduction)

The coronal plane kinematic parameters assessed in gait analysis are the valgus- varus (adduction/abduction) movements. Investigators have assessed parameters like peak adduction angle, mean adduction angle and adduction excursion in gait analysis. Weidow. (2005) found that greater knee adduction angles were associated with increased incidence of medial compartment knee OA. This has been confirmed in other investigations (Barrios 2010, Barrios 2012). This fits in with the relationship of adduction moments and osteoarthritis. Most of these investigators have assessed how these kinematic parameters affect the adduction moment which has been shown to significantly affect the progression of medial compartment osteoarthritis. Greater knee adduction has been shown to be good predictors of knee adduction moment (Barrios 2009). It has therefore been inferred that, the decrease in medial compartment knee cartilage thickness and an associated increase in peak adduction moment in the osteoarthritic knee may be related to knee adduction angle during level-walking. There has been some debate about the best predictor of medial compartment osteoarthritis amongst these coronal plane kinematic parameters. The finding that the peak adduction angle coincides with the peak knee adduction moment and that it correlated well with peak adduction moment makes it an extremely useful parameter to analyse (Barrios 2012). The use of all three kinematic parameters in investigations namely, peak adduction angle, mean adduction angle and adduction excursion increases the sensitivity of angular measures on the coronal plane.

4.8.3 Transverse plane kinematics

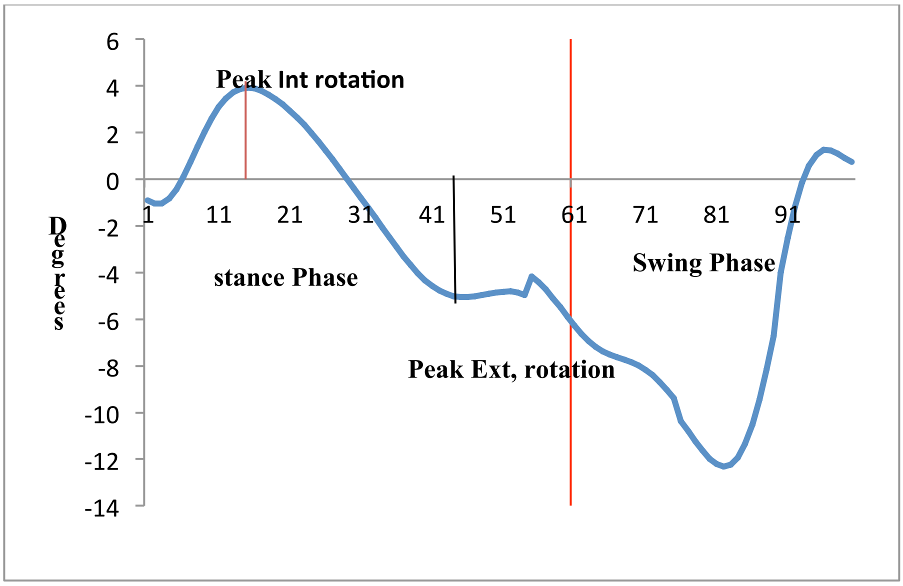


Figure 4.5.Transverse kinematics (peak internal & external rotation)

Transverse plane kinematic measures reported in gait analysis literature are internal and external rotation measured in degrees. The magnitude of rotations in stance is much smaller compared to the magnitude of flexion in the sagittal plane. Internal rotation has been reported to be reduced in osteoarthritic knees. This phenomenon has been described to be secondary to toe out gait which has been reported to be a compensatory pain relieving mechanism in osteoarthritis. There have been reports of toe in being an equally efficient mechanism in reduction of PKAM, but the authors concede that toe in may be a less natural mechanism as compared to toe out in osteoarthritis patients (Shull 2013).

4.9 Review of literature on kinetic analysis

Kinetics is the branch of biomechanics that deals with the joint forces that cause motion (Kirtley 2006). The kinematic data and anthropometric measures (segment mass, centre of mass and inertia) allow for the calculation of joint moments using an inverse dynamic approach. Joint moments are classified as external or internal. External moments are produced by external forces like ground reaction forces and inertial forces. The internal moments are generated by muscles, joint capsules, and ligaments, which counteract the external forces acting on the body. For the body segments to remain in equilibrium, the internal and external moments should be equal and opposite.

4.9.1 Coronal plane kinetics

Much of the research on the biomechanics of osteoarthritis of the knee has been concerned with measuring the knee joint load in the coronal plane using 3-dimensional gait analysis (Sharma 1998, Miyazaki 2002, Baliunas 2002). Dynamic knee joint load in the coronal plane can be estimated by calculating the external knee adduction moment (Miyazaki 2002). The external knee adduction moment is the product of the frontal plane component of the ground reaction force (GRF) and the perpendicular distance from the knee joint centre of rotation (Figure 4.7). The GRF vector passes from the centre of pressure (COP) under the foot to the vicinity of the centre of mass (COM) of the body (Figure 4.7). The typical adduction moment curve is a double humped curve. There are two peaks of adduction moment in the first and second half of stance with an intervening lower moment (Figure 4.6).

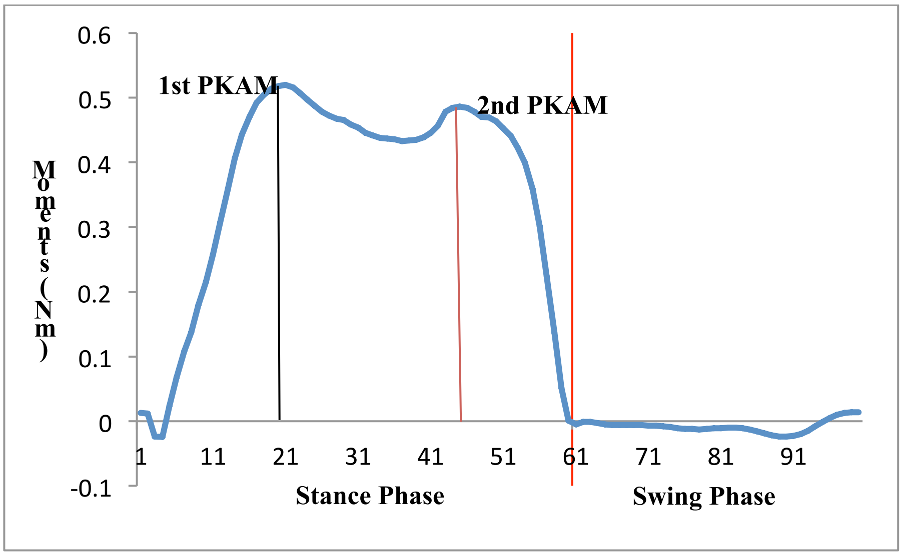


Figure 4.6.Coronal plane kinetics showing 1st & 2nd Peak

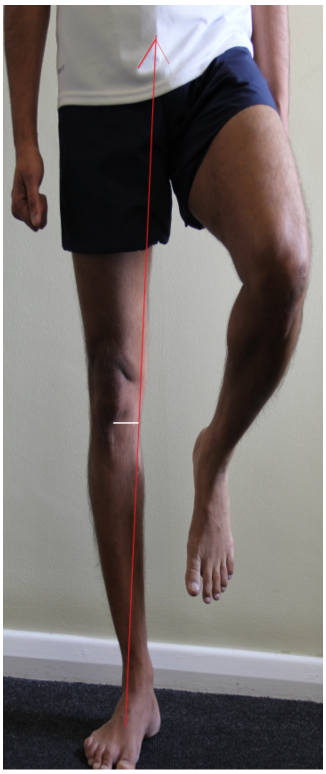


Figure 4.7 Representation of adduction moment {product of GRV (red) and perpendicular distance from knee centre (white)}

4.9.1.1 Knee adduction Moments

Knee adduction moments have been studied extensively as a parameter that reflects the dynamic loading of the medial compartment of the knee. Studies have reported a correlation between bone mass on the medial tibial plateau and peak knee adduction moment of the knee both in normal and osteoarthritic patients in keeping with what is expected as per Wolff's law, which states that bone is laid out in such a way to counter the line of stress (Hurwitz 1998, Wada 2001). This indicates that peak knee adduction moment is a valid loading parameter around the knee affecting the bone and articular cartilage. Even though patients with medial compartment osteoarthritis have been shown to have higher adduction moments, which may result in lower cartilage volumes, no relationship was found between the cartilage volume and adduction moments in normal patients (Jackson 2004)

Studies have reported higher knee adduction moments in subjects with medial compartment osteoarthritis compared to healthy knees (Sharma 1998, Miyazaki 2002, Baliunas 2002). On the adduction moment curve there are generally two peaks, which occur at the initial and terminal stance. Both peaks have been reported to be higher in osteoarthritic knees compared to healthy control subjects. The second peak knee adduction moment, occurring during terminal stance, has been found to be more variable and less distinct than the first peak, both in healthy controls and in individuals with osteoarthritis (Hurwitz 2002). Although the terminal stance peak knee adduction moment was found to be significantly different in individuals with certain radiographic grades of osteoarthritis, most investigators find the terminal stance peak adduction moment very variable for it to be used as a reliable measure in biomechanical investigation on patients with osteoarthritis of the knees (Mundermann 2005). The early stance peak adduction moment, which tends to have a higher peak is more reliable and has been studied much more extensively (Mundermann 2005, Thorp 2006). It has been found that a high peak knee adduction moment during gait cycle is a risk factor for the presence and severity of osteoarthritis in knees (Sharma 1998). It has also been found that a 1% increase in adduction moment resulted in approximately 6 times increase in the risk of progression of medial compartment osteoarthritis of the knee. There is good evidence to support the concept that a relationship exists between the knee adduction moment and disease progression which has prompted the use of insoles and valgus unloader braces in the management of medial compartment osteoarthritis (Draper 2000, Miyazaki 2002).

Studies have also reported the association between adduction moments and pain levels in patients with medial compartment osteoarthritis. Positive correlation has also been found between the peak adduction moment and WOMAC scores of which pain is a subgroup in patients with medial compartment osteoarthritis (Thorp 2007). Although peak adduction moments are associated with increased loading of the medial compartment and grade of arthritis, mild or early osteoarthritis show a decrease in the adduction moments. This is felt to be due to compensatory mechanisms like alteration in trunk lean and toe out that are associated with decreased adduction moments (Thorp 2006). This implies that progression of arthritis occurs when the regulating mechanisms adopted by the body fail in countering the increased loading. Moreover it appears that the higher adduction moments increase and tend to hasten the progression of osteoarthritis.

4.9.1.2 Peak Knee adduction moments and adduction impulse

Research in the field of medial compartment osteoarthritis has concentrated on measures that help to reduce the peak knee adduction moment (PKAM), in the hope that this intervention will reduce the medial joint contact force. A study using a force measuring knee prosthesis has revealed that reduction of PKAM does not necessarily decrease the medial joint contact forces (Walters 2010). This indicates that although peak Knee Adduction Moment is a useful and valuable surrogate measure for medial compartment loading, a more representative measure may be necessary.

Peak Knee adduction moment (PKAM) is a measure of loading at a single point of time. It is obvious that in tall curves the Peak Knee Adduction Moment would be high when compared to flat curves although the cumulative loads the knee has to bear may not be significantly different. From a tribologic point of view, both load and loading time are important variables that define the wear conditions of the joint, it is important to use a parameter that incorporates the duration of loading in the assessment of medial compartment loading. Because individuals with OA ambulate at slower speeds (Kaufmann 2000) and exhibit a prolonged stance phase as compared with healthy individuals (Al Zahrani 2002, Gok 2002), both the magnitude of the knee adduction moment and the duration of the adduction moment at the knee deserve sufficient if not equal importance. Studies analysing artificial bearings have shown that the time integral of load is as important as the load magnitude itself in the description of wear (Thorp 2006).

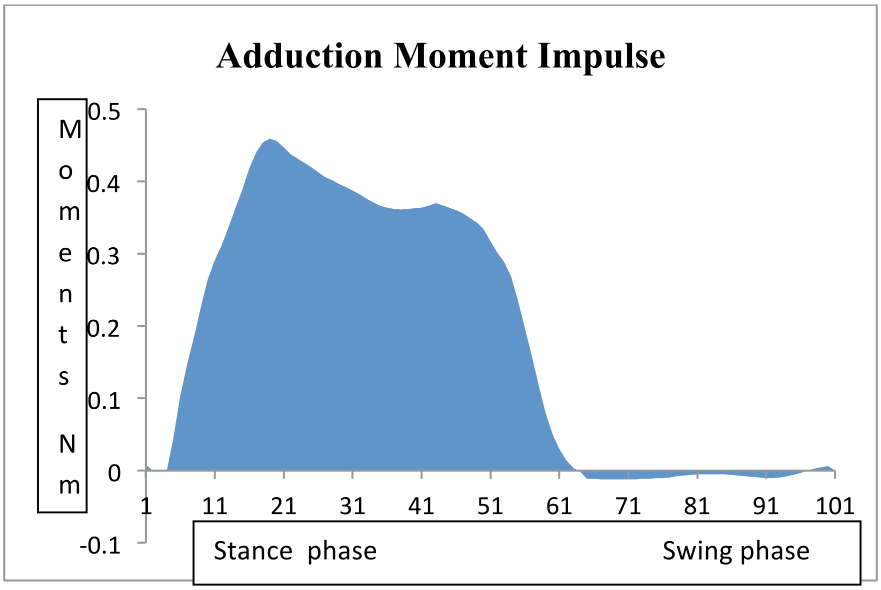


Figure 4.8 Adduction impulse

The knee adduction angular impulse is the moment time integral for the adduction moment curve.

It is calculated as follows,

Add Imp = ∫ M (t) dt, where M is adduction moment and t is time.

Moment–time integrals has been previously used to describe the distribution of bone in the proximal tibia and patello femoral loading (Thorp 2006). The use of adduction angular impulse (Add Imp) as a useful measure of medial compartment loading and was first described by Thorp et al in 2006. Since then it has been used by researchers and has become a valid measure of cumulative loads experienced by the tibial plateau during the stance phase (Thorp 2006, Robbins 2008, Block 2010). It is intuitive to expect that if individuals with knee osteoarthritis display larger than normal peak knee adduction moments, the knee adduction angular impulse throughout stance is also likely to be of greater than the normal magnitude, particularly as the stance time in knees with osteoarthritis is longer. As progression of osteoarthritis is related to increased load (Andriacchi 2004), the adduction angular impulse should influence the progression of medial compartment osteoarthritis significantly.

In a recent series it was found that increased adduction moment impulse was a better predictor of cartilage volume loss measured using MRI scans than peak knee adduction moment over a twelve month period (Bennell 2011). Other authors have published the value of adduction angular impulse measurements in the progression and severity of medial compartment osteoarthritis (Kean 2012).

4.9.2 Sagittal Plane Knee Moments

Sagittal plane kinetic parameters are very important in determining the knee joint reaction to dynamic loading. They are bigger in magnitude when compared to coronal and transverse plane moments. Knee joint reactions to dynamic loading in the sagittal plane can be assessed by analysing the external sagittal plane moments.

The typical sagittal plane knee moment waveform during the stance phase of gait begins with an external knee extension moment at initial contact, progressing to an external knee flexion moment in early stance phase and an external knee extension moment in late stance phase (Winter 1990, Olney 2005).

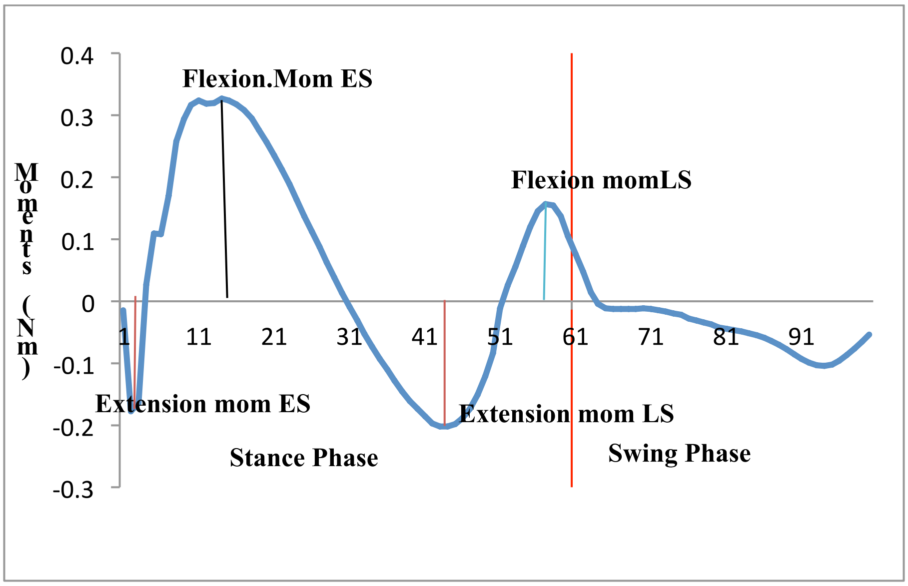


Figure 4.9 Flexion- Extension Moments in Early stance (ES) & Late stance (LS)

As the knee is extended at initial contact, the ground reaction force vector is anterior to the knee joint, creating a small external extension moment. The hamstring muscles (knee flexors) are active to counteract this external moment. Following initial contact, the knee flexes approximately 15° and the GRF vector falls posterior to the knee, creating an external flexor moment. This moment is opposed by the quadriceps muscles (knee extensors) which contract eccentrically at this point preventing the knee from flexing further during load transfer to the limb in stance. From heel-off to toe-off, the knee flexes to approximately 30º. The GRF vector falls anterior to the knee joint at this point in the gait cycle creating a late stance external extension moment. The knee flexor muscles counteract this moment (Winter 1990, Olney 2005).

Several studies have investigated sagittal plane lower extremity kinetics in people with medial compartment knee osteoarthritis and compared them to those of healthy older adults (Kaufmann 2001, Baliunas 2002, Gok 2002, Mundermann 2005). The peak knee extension moment is the most common sagittal plane kinetic variable that has been studied in relation to osteoarthritis of the knees, but findings are inconsistent. Studies have shown smaller peak knee extension moment (Kaufman 2001, Zeni 2009) while others have shown greater peak knee extension moment (Al-Zahrani 2002, Gok 2002) or no differences (Mundermann 2005) in osteoarthritic knees compared to knees in healthy controls. The peak knee extension moment provides a reflection of how much torque the knee extensors are producing to counteract the external knee moment created by the ground reaction force vector and its moment arm to the knee joint centre. The variations in vertical GRF peak values related to different walking speeds may be responsible for the inconsistent findings on peak knee extensor moment in knee OA patients compared to healthy controls.

Conflicting findings have been reported concerning the early stance phase flexion moment. Several researchers have found that individuals with medial compartment knee osteoarthritis had lower knee flexion moments compared to healthy controls (Kaufmann 2001, Astephan 2008). Conversely, other researchers have reported higher knee flexion moments in osteoarthritic knees compared to healthy controls (Gok 2002, Al zahrani 2002). Finally, there have been reports of no significant differences in the external knee flexion moment in early stance between osteoarthritic knees and control groups (Baliunas 2002, Mundermann 2005). These inconsistencies may be due to variations in peak knee flexion angle and gait velocity in the patients investigated.

Findings regarding the late stance extension moment are more consistent. Authors have reported either lower knee extension moments in people with medial compartment knee osteoarthritis compared to healthy older adults or no difference between groups (Mundermann 2005, Astephen 2008).

Although the extension and flexion moments in stance have been studied extensively and have significant influence on loading of the knee, the sagittal plane moments have not been investigated as thoroughly as the coronal plane moments, possible due to the inconsistencies mentioned previously. The variations in sagittal plane moments can be ascribed to it being sensitive to minor degrees of fixed flexion deformity and variation in force generated by the strong extensors and flexors around the knee.

4.9.3 Transverse plane kinetics

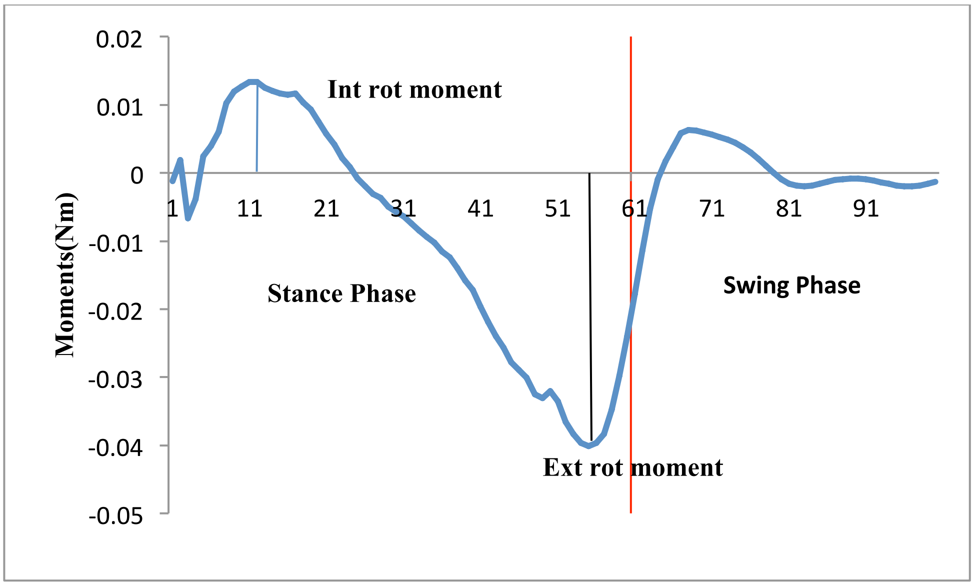


Figure 4.10 Transverse kinetics (rotation moments)

The rotation moments are the smallest of the three moments in magnitude and also the least reliable, but they have a significant role in the progression of osteoarthritis. Andriacchi (2006) has suggested that changes in the transverse plane mechanics at the knee may initiate degenerative changes in the articular cartilage by placing increased loads on regions that were not previously conditioned for these different load levels.

Few studies have considered the moments about the knee in the transverse plane. However, authors have reported variations in knee rotation moments compared to healthy controls (Gok 2002). Gok found increased external rotation moments in subjects with osteoarthritis, while Brandon reported a decrease in internal rotation moment in subjects with osteoarthritis of the knee (Brandon 2011). However, investigations on knee moments in the transverse plane did not find a significant difference between the osteoarthritis and control groups (Kaufman

2001, Landry 2007). These discrepancies in values reported in the literature may be due to the fact that the transverse plane moments are smaller in magnitude as a result more sensitive to small alterations in the resultant forces that govern kinetics in the transverse plane.

Chapter 5

Outcome measurement following unicompartmental knee replacement

WOMAC

Modified Knee Society Score

Measure of alignment

This chapter outlines the importance of measurement of clinical and radiographic outcomes following replacement surgery of the knee. The outcome measures used in the investigation has been discussed in detail with the relevant literature.

5.1 Measurement of outcomes after replacement surgery of the knee

Measurement of health status is important both in medical practice and research. One of the key factors in the practice of evidence-based and cost-effective medicine is the detection and proof of the effects of a particular intervention. Evaluation of knee osteoarthritis and the efficacy of interventions, both medical and surgical depend on the effective use of Health status measurement tools. In research and practice environments, reliability, validity, and responsiveness are essential attributes of these health status measurement tools. In clinical practice brevity, simplicity, and ease of scoring are extremely important as well (Bellamy 1999).

Different scoring systems are available for use. Some, like the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC), can be entirely patient reported without any objective measure for assessment of function. Others, like the Modified KSS (Knee Society Score) have some objective measures like stability and range of motion which is measured by an individual. The objective measures are valuable to surgeons to measure the improvement in anatomical parameters like range of movement and stability of joint that a surgical procedure can make. Although the relative merits and demerits of patient reported outcome measures have been discussed extensively in literature, they do not provide the same level of information about the relationship between function and anatomical signs and measures as well as the objective scores do, but are more likely to reflect the effect of the procedure on patient function.

5.2 Characteristics of outcome measures

An outcome measure is a common language that can be used by clinicians and researchers that allows comparison between subjects (or groups) and the same subject (groups) at different times. An outcome measure must provide an objective measure (Davies 2002) of the subject's impairment which can be compared with other similar subjects and to the same subject at different points of time. It should therefore be applicable before and after an intervention to measure its effect which means an outcome measure must be valid, reliable and responsive (Kreibich 1996).

Validity refers to the extent to which the outcome tool measures the component that it is designed to measure (Kreibich 1996, Finch 2002). There are three basic types of validity - content validity, criterion validity and construct validity (Johnston 1992). Content validity indicates whether the tool measures the component items of a relevant feature that an examiner wants to assess in a subject. Criterion validity is the extent to which the assessment of variables using a tool is similar to that obtained by standard procedures which are set to assess the same variable. Construct validity refers to the extent to which the tool produces similar results to the preformed theories about domains which cannot be measured using standard procedures (Finch 2002).

Reliability refers to the extent to which consistent results are produced after repeated measures (Seale and Barnard 1998) and hence reliability of the tool and examiners must be established. There are two types of reliability – inter rater reliability and intra rater reliability. Inter rater reliability refers to the extent to which a tool produces consistent results when used by different examiners during same instance of examination and mainly prevents an examiner from being biased on the tool (Johnston 1992, Hicks 1995). Intra rater reliability or test retest reliability refers to the extent to which a tool produces consistent results when used by the same examiner during two different times (Johnston et al 1992) provided there is no intervention done between the assessments. A responsive outcome measure is said to be able to predict changes in patient's impairments due to interventions over a period of time (Kreibich 1996). It is the character of a tool to measure even small changes in the patients' condition which is important to establish the effectiveness of a treatment.

Dimensions of health deemed to be important to patients include pain, function, quality of life, and activity level. Various scoring systems available to clinicians and researchers in the evaluation of osteoarthritis use these factors to achieve comparison between population groups, and in the same group at different points of time. This may be to evaluate the natural history or efficacy of intervention in a group of patients. Although different scoring systems use essentially the same parameters, the numerical weightage given to individual parameters can result in wide variations for example; how much does pain on climbing stairs contribute to the overall disability that the score computes. Moreover the use of different scoring systems by individual authors, make it difficult to compare different reports.

5.3 Choice of Outcome measure

For purposes of this investigation two commonly accepted outcome measures were chosen, namely Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) and modified Knee Society Score. Although different scoring systems provide different advantages and disadvantages, a consensus was reached among representatives of the US Food and Drug Administration, European League Against Rheumatism, the World Health Organization/International League of Associations for Rheumatology, and the Group for the Respect of Ethics and Excellence in Science who were polled at the OMERACT III conference, recommending the use of the Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) for the assessment of knee osteoarthritis (Bellamy 1997). This has been reflected in orthopaedic literature since, as the WOMAC is very commonly used and is generally recommended as the most sensitive, condition-specific instrument for the assessment of interventions in osteoarthritis of the lower extremities in the last two decades (Bellamy 1988, Bellamy 1995, Ehrich 2000, Escobar 2007, Alzahrani 2011). Moreover the WOMAC scores have been extensively studied to prove its content, construct and criterion validity with appropriate normalisation procedures so that the scores can be compared between population groups (Bellamy 2012). All musculoskeletal interventions involves trade-offs and only the patient can truly assess the extent to which the result of the intervention has optimised the outcome (Bailey 1995, Wright 1997, Wylde 2008). Although the patient reported outcome measures reflect the satisfaction rates and improvement in disability, the perceived improvement of function by the patient may not necessarily translate into objectively measurable improvements. This is demonstrated by discrepancies that exist between clinician- and patient-derived health-related quality-of-life tools (Janse 2004, Mäntyselkä 2001).

5.4 Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC)

The WOMAC is a disease-specific self-report questionnaire for measurement of the symptoms of osteoarthritis of the hips and knees. It is reliable, valid, and sensitive to the changes in the health status of patients with osteoarthritis of the knee. Initially developed in 1982, the WOMAC has undergone multiple revisions (most recent version 3.1). It is available in 5-point Likert, 100-mm visual analog scale (VAS), and 11-box numerical rating scales (Ornetti 2011). It has three subscales. 1) pain; severity during various positions or movements, 2) severity of joint stiffness and 3) difficulty performing daily functional activities. We used the 3.1 Likert version with five response levels for each item, representing different degrees of intensity (none, mild, moderate, severe, or extreme) that were scored from 0 to 4. The range for possible subscale scores in the Likert format are: pain (5 items; 0–20), stiffness (2 items; 0–8), and physical function (17 items; 0–68). If 2 or more pain items, both stiffness items, and 4 or more physical function items are missing, the response should be regarded as invalid and the deficient subscale(s) should not be used in analysis (Bellamy 1995). The final score for the WOMAC ranges from 0-96 on the Likert version.

Responses on the WOMAC can be dichotomised according to the OMERACT-OARSI responder criteria for osteoarthritis (Pham 2004), i.e. treatment responders are defined as those participants achieving ≥20% improvement in both pain and physical function scores and an absolute change of ≥10, or ≥50% improvement in pain or physical function scores and an absolute change of ≥20 on the WOMAC. The WOMAC appears to be responsive to change following surgical and nonsurgical interventions for knee osteoarthritis. In patients with knee osteoarthritis, large effect sizes are consistently reported on all 3 subscales up to two years following replacement arthroplasty of the knee. The patient-acceptable symptom state has been determined to be 31.0 (95% confidence interval 29.4–32.9) for the function subscale in people with knee osteoarthritis with 39 being the threshold for replacement arthroplasty (Tubac 2005).

Overall, test-retest reliability of the WOMAC pain subscale has been variable across studies but generally meets the minimum standard; test-retest reliability has been more consistent and stronger for the physical function subscale, but the stiffness subscale has shown low test-retest reliability (McConnell 2001). While one study found the pain subscale to demonstrate good item separation and unidimensionality in patients with knee osteoarthritis (Wolfe 1999), a subsequent study found that a reduced pain subscale (night pain and pain on standing removed) fit the Rasch model and provided more stable results over time and between patients with knee osteoarthritis and those who have undergone joint replacement (Davis 2003). The function subscale demonstrates more variability. Although found to have good item separation and unidimensionality in knee osteoarthritis, function items for performing light chores, getting in/out of a car, and rising from bed have been found to be redundant

(Wolfe 1999). Similarly, Davis et al (Davis 2003) suggested a 14-item function subscale, with items for heavy domestic duties, getting in/out of the bath, and getting on/off the toilet removed. Although authors have debated the necessity and weightage of individual questions, we used the WOMAC Likert version 3.1 in its entire form without any modifications.

5.5 The Modified Knee Society Score (1993)

Measurement of outcomes in the field of Total Knee replacement arthroplasty, was pioneered by Insall et al. in North America (Insall 1976). The original American Knee Society Clinical Rating System was adopted in 1989 and later modified in 1993 (www.kneesociety.org). Although the parameters remained the same the weightage for individual parameters changed during the modification. This score has been widely supported and adopted by orthopaedic surgeons in North America and all over the world (Konig 1997, Bach 2002, Davies 2002). This version of Knee society score expresses the outcome derived from the severity of pain reported by the patient and the alignment, stability, and range of motion of the knee objectively measured by an assessor and a Knee Society Function score, based simply on the patient's ability to walk and climb stairs. This version of the score was originally made for assessment of total knee replacements.

The application of these methodologies to compare different assessment instruments has shown, although the Knee Society scoring system is concise and user-friendly, but the Knee Score component demonstrates poor reliability with acceptable responsiveness, while the Function Score component demonstrates good reliability with questionable responsiveness (Bach 2002, Davies 2002, Lingard 2001). These studies demonstrated poor correlation between the items of the Clinical KSS, suggesting that a good score in one part of the scale may not reflect a good score in another, making final interpretation difficult. For example, a score of 80 points in the Clinical KSS may be given to a patient without symptoms of pain, with range of motion from 0° to 25° of knee flexion, normal alignment, and without signs of joint instability, or to a patient who presents slight or occasional pain when climbing or descending stairs, 0° to 130° of knee flexion, normal alignment, and without signs of joint instability. These individuals clearly obtained considerably different results (Lingard 2001).
Other studies evaluating the knee society score showed there was good correlation for the items "Pain", "Range of Motion" and "Flexion contracture"; weak correlation for both items "Mediolateral stability" and "Extension deficit", and no correlation for the items

"Anteroposterior stability" and "Alignment". In the functional component of KSS, there was good correlation for all the items analysed individually (Martimbianco 2012). Bach et al. demonstrated strong inter-observer correlation for the variables "Range of motion", "Flexion contracture" and "Extension deficit". Low inter-observer correlation was also observed in the analysis of the "Alignment" item. This is difficult to measure with the use of a simple goniometer. As the KSS is calculated using a clinical scoring algorithm that includes both positive and negative items, statistically it is inappropriate to test the internal consistency of these values.

The validity of the "Pain" item of the Clinical KSS and of the Functional KSS was established by the conclusion that they presented slight correlation with the analogous domains of the WOMAC. For the above mentioned drawbacks, the Knee society has reviewed the KSS and have recently come up with a modified score (Scuderi 2012) As this became available only after the start of the investigation , the 1993 modified version was used in this study.

Although the knee society score has not been extensively validated like the WOMAC it has been used in the assessment of unicompartmental knee replacements. Although the patients that undergo unicompartmental knee replacements would naturally be penalised for deductions in alignment, the knee society score was used in the present investigation.

5.6 Measurement of alignment in knees; Static or Dynamic?

Many different approaches have been proposed over the years to describe and measure alignment (Moreland 1987, Hsu 1990), but the differences between the various measures have made it difficult to compare or correlate the results of independent studies. One of the commonest sources of error in measurement of alignment is the difference in rotation of the limbs at the time of radiography (Cooke 2009). Limb positioning is prone to errors due to a lack of standardization during patient set-up for imaging. These errors may be exacerbated in the presence of limb deformities, especially those that obscure reference bone landmarks useful in the control of rotation. Clearly, variations of limb position, especially rotation, significantly influence the alignment measures (Sanfridsson 2001). Long leg radiographs of the whole limb in stance are ideal for measuring alignment of the knee, in terms of both the Hip Knee Ankle (HKA) angle and the other joint angles especially in the presence of deformities. As long leg alignment views are not done as a routine, the assessment of alignment at the knee tends to be done on short views. Although an approximation of the femorotibial alignment can be done from these views, mechanical axis cannot be drawn on these images (Moreland 1987, Hsu 1990, Kraus 2005). Correlation analyses between the femorotibial angle from short knee radiographs and the mechanical axis angle from long leg alignment radiographs are reported values of r ranging from 0.65 to 0.88 (Kraus 2005, Issa 2007). Thus although the femorotibial angle measured on standard short radiographs is sensitive and specific enough to differentiate varus and valgus knee alignment in most cases it is not sufficient for the purposes of achieving precision in the field of research.

The varus angulation is apparently lower when measured with the knee in full extension compared to when the knee is in semi flexion (Cooke 2009). As patellar malalignment is quite common in arthritic knees, especially in the presence of varus deformity to align the limb for radiography using the orientation of the patella can be error prone (Harrison 1994). In such knees, to align the limb according to a forward-pointing position of the patella can result in the flexion angle of the knee being outside of the sagittal plane (Cooke 1990). The shift of the flexion angle outside the sagittal plane can lead to a lateral shift in the location of the tibial tubercle in the radiograph which reduces the reliability of this landmark as a positional reference (Cooke 1990). A frame platform approach with a fixed foot position has been described to avoid this problem, and get identical positions of the knee for the purposes of radiography helps in the assessment of significant deformities (Cooke 2009). In the patient population with unicompartmental knee osteoarthritis under consideration for this investigation, where comparisons between preoperative and postoperative alignment was assessed this is not a significant issue.

The load-bearing mechanical axis is a line drawn from the centre of the femoral head to the centre of the talus on long leg radiographs. In neutrally aligned limbs, this line passes through a midpoint between the tibial spines. In neutrally aligned knees, the medial compartment bears a resultant 60% to 70% of the load across the knee during weight-bearing (Andriacchi 1994). This asymmetry of loading between the medial compartment and the lateral compartment may play a role in the predisposition of the knee to medial compartment osteoarthritis (Ledingham 1993). In a varus knee, the mechanical axis passes medial to the knee creating a moment about the joint, which further increases the force across the medial compartment. It is recognised that neutral alignment in majority of the population is typically

2 degrees of varus (Kraus 2005, Cooke 2007). Malalignment provides only a static assessment of the loads in a single plane (coronal) of joint activity. The dynamics of gait involve multiple forces that stress the knee in several planes simultaneously. During the stance phase of gait, the ground reaction force acting on the limb passes medial to the axis of the knee joint. The perpendicular distance from this force vector to the axis of the knee joint constitutes a moment arm for the application of an adduction moment (Andriacchi 1994). In a varus malaligned knee, the peak adduction moment is expected to rise, increasing the load across the medial compartment (Tetsworth 1994). The adduction moment might also be affected by habitual postures during locomotion, or by more distal malalignments, such as tibial or calcaneal varum. In the presence of existing osteoarthritis of the knee, abnormal alignment is associated with accelerated structural deterioration in the compartment that is subjected to abnormally high compressive stress. Varus malalignment has been shown to predispose the medial compartment of the knee to a fourfold amplification of focal progression of osteoarthritis (Sharma 2001). The differences in joint forces and joint stress during functional activities may assist in explaining the dissociation between the structural findings on radiographs and the level of pain experienced by the patient. It has been reported that radiographic alignment angles increase in the varus direction when moving from supine to double-limb standing, to single-limb standing (Specogna 2007). Therefore, single-limb stance, when peak adduction angle and moment typically occur, might be better represented on radiograph when radiograph is taken in single-limb stance rather than double-limb stance. Malalignment has been shown previously to be a predictor for functional decline in knees with osteoarthritis and may play a role in its progression.

The assessment of malalignment on radiograph is a static measure and does not fully represent the loading of the knee dynamically. It has been suggested that the knee adduction moment would be more strongly related to dynamic measures of knee alignment than to radiographic alignment (Sharma 2006). Dynamic knee alignment in the coronal plane (varus/valgus) can be assessed by the kinematic data obtained in the coronal plane during three-dimensional gait analysis. Peak knee adduction angle during stance has been reported to correlate highly with radiographic alignment (Hunt 2008). It is intuitive that adduction moments measured on gait analysis will correlate with adduction angle measures at the knee, be it mean adduction angle, peak adduction angle or adduction excursion. Recent reports have found that that knee adduction angle at the time of peak adduction moment (Barrios 2009) and shank adduction angles (Foroughi 2010) were significantly related to adduction moments. Peak knee adduction is of interest as this is the greatest instance of limb malalignment during an episode of stance. The mean adduction angle merits interest as a value representing alignment throughout stance. The mean adduction angle may represent the kinematic variable most closely related to the Hip Knee Ankle (HKA) angle and Mechanical axis (MA) measurements on the long leg alignment films. It is likely that the peak adduction moment would show a stronger correlation to peak adduction angle while the mean adduction angle would be less likely to. The mean adduction angle is more likely to correlate with the adduction impulse. In previous epidemiological studies, researchers have quantified radiographic knee alignment in an attempt to evaluate the influence of alignment on disease progression. Thus, these results are important in that dynamic, rather than radiographic, knee alignment may relate more closely to disease progression.

WOMAC is the most extensively validated and reported patient reported outcome measure. As this does not measure objective outcomes, the modified knee society score was used in the investigation. Even though the knee society score was formulated to measure the outcomes following total knee replacements, it has been used to report outcomes following unicompartmental knee replacements.

The Hip Knee Ankle (HKA) angle and location of the mechanical axis on the tibial plateau are well established measures of static alignment. The static measures and dynamic alignment measures detailed in the previous chapter were measured in this investigation.

Chapter 6

Description of methodology and outcome measurement in study II

This chapter describes the design of the study, collection of data, conversion of data and statistical analysis.

6.1 Study Setting

All patients listed for medial unicompartmental knee replacement arthroplasty as treatment for medial unicompartmental knee osteoarthritis were invited to join the study. Although the suitability for unicompartmental knee replacement was based on clinical and radiological assessment, the final decision was made at the time of surgery. If at the time of the operation it was felt that osteoarthritis was not limited to the medial compartment, a total knee replacement was performed. These patients who went through preoperative assessment but had a total knee replacement were invited back for postoperative assessment, but were not included in the final analysis. Not all patients following total knee replacements attended postoperative gait analysis.

6.2 Participants

Twenty three individuals with osteoarthritis of the medial compartment of the knee joint participated in this study. Written consent (Appendix A) was obtained after providing them the information sheet (Appendix B). The study had ethics committee approval from the North Staffordshire Ethics committee (Appendix C). The original study was set up at the University Hospitals of North Staffordshire, and some data collection was done, unfortunately due to unforeseen circumstances the gait lab was closed down and the study was transferred to Royal Derby Hospitals. The data collected at University Hospitals of North Staffordshire were not used. Further, approval of the ethics committee and Research and development department at the hospital was obtained for this purpose (Appendix D).

Exclusion criteria included other disorders which might affect gait such as rheumatoid arthritis, heart disease, or any neurological conditions including stroke or Parkinson's disease, and post traumatic secondary osteoarthritis. Patients with cognitive impairment that would preclude obtaining informed consent and inability to ambulate without a walking aid were excluded. The patients who underwent total knee replacements at the time of the operation were given the option of attending the second gait analysis. All patients who had medial unicompartmental knee replacements underwent identical post-operative rehabilitation program.

6.3 Data Collection

6.3.1 Site for data collection

For all participants clinical scoring and instrumented gait analysis was conducted at the Derby Gait and Movement Laboratory (Derby Hospitals NHS Foundation Trust), London Road Community Hospitals, Derby. Radiological assessment was done using the radiographs obtained as part of the preoperative assessment for these patients. This was done at the Radiology department of the Royal Derby Hospitals, Derby as part of the out - patient follow - up.

6.3.2 Clinical Assessment of Pain and Function

All patients were scored using Western Ontario and McMaster Universities Arthritis Index (WOMAC) and Knee Society Scores (KSS) (Appendix E). WOMAC was used after obtaining appropriate licence. This was repeated post operatively at a minimum of six months after the surgery.

The Western Ontario McMaster Universities Osteoarthritis Index (WOMAC) measures joint pain, stiffness, and difficulty in function in the patients with knee osteoarthritis. WOMAC questionnaire consists of twenty four questions pertaining to joint pain (5 questions), stiffness (2 questions) and physical function (17 questions). Each question has a sub-scale ranging from 0 to 4; with 4 representing extreme pain, stiffness and functional difficulty. The scores were then summed to produce total scores for each of the three measures as well as a total score.

The knee society score has two components, the knee score and the function score. The knee score assesses the pain and measures the range of movement, stability and alignment with deductions for each detrimental finding. Pain is assessed while walking (35 points) and while climbing stairs (15 points). The range of movement scores 1 point for every 8 degrees.

6.3.3 Radiographic assessment

All patients underwent radiographic assessment with antero posterior, lateral and skyline views and long leg alignment views.

Alignment of the knee joint was assessed on Long leg alignment films. These were obtained close to the preoperative and postoperative gait analysis. All long leg alignment films were obtained as per a standardised hospital protocol. The mechanical axis was drawn according to the modification of the protocol of Moreland et al (Moreland 1987). The mechanical axis was drawn as a straight line connecting the centre of the femoral head with the centre of the talus. The alignment at the knee joint was assessed using the HKA angle and the zone on the tibial plateau through which the mechanical axis passed. The differences in the HKA angle and zone of location of mechanical axis between the preoperative and postoperative groups were compared and the effect on loading of the tibial plateau was assessed.

6.3.4 Gait Analysis

All patients underwent gait analysis evaluation to compute the kinematic and kinetic parameters of the knee pre operatively and post operatively following the unicompartmental knee replacement arthroplasty. These analyses were carried out at the Derby Gait and Movement Laboratory (Derby Hospitals NHS Foundation Trust). The gait analysis laboratory consisted of an 12 infra-red camera movement analysis system operating at 100 Hz (BTS, Milan). The cameras were positioned such that the spatial location of the markers on patients was captured as they walked along a 10m walkway. Before commencing any data collection sessions, the laboratory was calibrated using calibration routines according to the manufacturer's instructions and protocols. A number of 15mm diameter markers were positioned on the pelvis and lower limb. The participant was then asked to stand in the centre of the room to allow the position of these markers to be captured by the cameras for a standing calibration file. During the anatomical calibration procedure, the participants had the markers positioned as shown in the table 6.1. The calibration marker was removed leaving the dynamic markers in situ. Each participant was requested to walk at a self selected walking velocity along the 10m walkway. This was repeated until the participant had managed a clean foot strike of the force plate of the limb under test. The start point for each walking episode was altered such that a clean foot strike was achieved. The subjects undergoing the gait assessment was not informed of the reason why the start point was altered till after the acquisition of data. The force plate (Kistler, Switzerland) measures triplanar forces at every foot strike. The process was repeated for both limbs till satisfactory data was obtained.

Table 6.1 showing Marker positions on the pelvis and lower limb

Number	Position	Motion Marker	Calibration Marker
1	Sacrum	X	X
2	ASIS	X	X
3	Greater Trochanter	X	X
4	Lateral Thigh Wand	X	X
5	Lateral Femoral Epicondylar notch	X	X
6	Fibular head	X	X
7	Lateral Leg wand	X	X
8	lateral Malleolus	X	X
9	Metatarsal Head	X	X
10	Posterior Heel		X

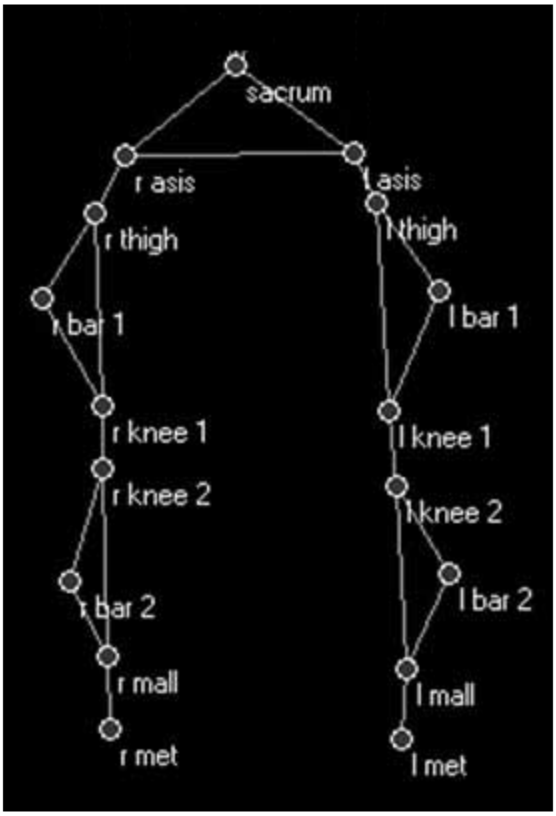


Figure 6.1 Diagrammatic Representation of placement of markers as per Davis Protocol.

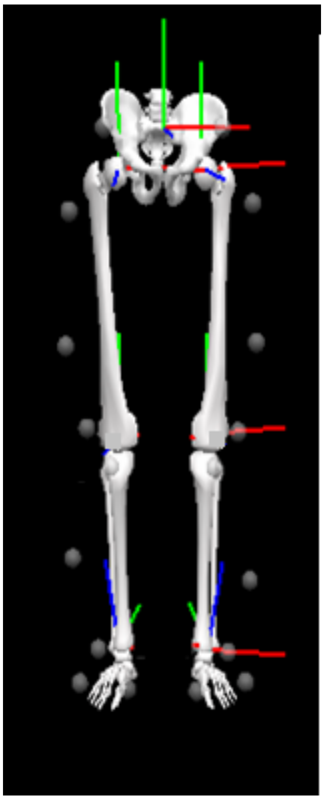


Figure 6.2 Completed skeletal model used in the calculation of gait parameters

The standard ELICLINIC software (BTS, Milan) was used to gather and process the raw motion (temporo-spatial parameters) and force plate data (gravitational and ground reaction forces). An inverse dynamics procedure was applied to the gathered data to generate external knee joint moments during stance phase. Full gait analysis was undertaken till three clean foot strikes on the force plate of each limb were measured.

The following biomechanical outcomes were recorded,

Kinematic outcomes

• Knee flexion / extension
• Knee adduction / abduction
• Maximum external/internal rotation of the knee

Kinetic outcomes

• Knee flexion / extension moment
• Knee adduction moment
• Knee Adduction moment Impulse
• Knee rotation moment

6.3.4.1 Time distance (Temporospatial) Parameters

Data gathered from six walking trials (at least 3 for each side) were used to obtain the average of the following temporal-spatial parameters: gait velocity (m/s), stride length (m), double limb support time (seconds), and cadence (steps/min) for each patient. The average values for patients pre operatively and post operatively after medial unicompartmental knee replacement was calculated and the difference analysed.

6.3.4.2 Kinematic parameters

Parameters in coronal, sagittal and transverse planes were measured and analysed. The coronal plane kinematic alignment parameters were measured and analysed in detail to assess the effect of kinematic alignment on kinetics. The mean adduction angle through the entire stance phase, the peak adduction angle and adduction excursion were recorded for all knees preoperatively and postoperatively.

6.3.4.3 Kinetic parameters

The external knee joint moments in the coronal, sagittal and transverse planes were recorded for the entire gait cycle divided into 100 points representing 100% of the gait cycle was calculated. They were compared between preoperative and postoperative groups. Peak external knee adduction, flexion, and extension moments were calculated from the average moment waveforms of three gait trials. For external knee adduction moment, extension moment and flexion moment, the highest peak was used in the analysis. The Angular adduction Impulse, which is the moment time integral of the adduction moment graph was calculated. It is the area under the curve and represents the cumulative load during stance phase. All values of external joint moments were normalized to body weight and height, to allow comparison between patients and evaluate average values for groups.

By convention knee extension, knee adduction and knee internal rotation were represented as positive values.

6.4 Procedure

Once the potential participants were identified in clinic, the primary researcher discussed the study objectives and procedure with them, and if they were willing to take part, a detailed information sheet (Appendix 6) was supplied to individual patients. All participants then signed the informed consent (Appendix 1). Testing was conducted at the Derby Gait and Movement Laboratory (Derby Hospitals NHS Foundation Trust), London Road Community Hospitals, Derby. The gait assessment session along with the WOMAC and modified KS score collection lasted approximately 1 hour.

Participants' weight and height were measured using a regular scale and tape measure. Participants were then asked to change into shorts for the walking tests. Surface markers were positioned on their skin at the foot, ankle, leg, thigh, hip, lower back using double sided adhesive tape. They were asked to walk along an10-metre indoor walkway at a comfortable speed as the cameras detected the movement of the surface markers. Participants were provided with rest breaks in between walking trials if and when needed. Six good trials were collected from each participant and the average of these trials was used for final analyses.

6.5 Statistical Analyses

The reliability of measurement of individual gait parameters was calculated using intra class correlation coefficient (ICC). ICC will range from 0 to 1, with values closer to one representing the higher reliability. We based the value of ICC on the recommendation by Chinn (1991) that any measure should have an intra-class correlation coefficient of at least 0.6 to be useful. The ICC is useful when comparing the repeatability of measures which use different units, as it is a dimensionless statistic.

The standard error of measurement (SEM) was calculated for each parameter using the formula, $SEM = SD \sqrt{1} - ICC$ (where SD is the standard deviation of the set of observed test ICC is the intra class coefficient), to allow us to define what change would be considered significant.

The clinical parameters namely the WOMAC and KSS were compared for the differences in pre and postoperative measures. The differences were analysed using paired t –tests. Radiological alignment was compared between preoperative and postoperative groups. Paired t- tests were used to determine differences in time and distance parameters of gait (gait speed, stride length, double limb support time, and cadence) and knee alignment. Paired t- test were used to determine if the knee adduction moment (KAM), knee adduction angular impulse (Add Imp), knee sagittal moments, kinematics including knee flexion/extension, abduction/adduction and rotation were significantly different between the preoperative and postoperative measures. The effect of coronal plane alignment on coronal (frontal) plane moments was analysed. The patients were analysed predominantly in two separate groups one where the alignment correction was less than 3 degrees, and another where the alteration in alignment was greater than 3 degrees. The alpha level (p-level) was set at 0.05 for significance testing. Regression analysis was carried out to assess the predictive value of alteration of alignment on medial compartment loading. Multiple regression analysis was performed to assess the effect of static and kinematic alignment on the loading parameters and the predictive value of every unit change of alignment on medial compartment loading was calculated. Statistical analysis was performed using Microsoft Excel 2010 and SPSS software (version 20 SPSS Incorporated, Chicago, Illinois).

Chapter 7

Results of Gait Analysis, clinical and radiographic outcome measurements

7.1 Demographic Characteristics

Twenty two patients with radiological medial compartment knee osteoarthritis (mean age 65.31 ± 4.94 years, 6 women) were enrolled and took part in the early assessments. This amounted to twenty five knees. Six of these patients (7 knees) were deemed unsuitable for medial unicompartmental knee replacements and underwent total knee replacements. This left data on eighteen knees for analysis. All the data was assessed for normality using histograms, q-q plots and Kologomorov – Smirnov statistic. Parametric data was analysed using paired t-test. Non parametric data was analysed using paired Wilcoxon signed rank test.

7.2 Clinical assessment

Clinical assessment was done using Western Ontario and McMaster Universities Arthritis Index (WOMAC) and Modified Knee Society Score (Insall 1993).

7.21 Western Ontario and McMaster Universities Arthritis Index (WOMAC)

All patients had preoperative and post-operative scores. All responses were made in the presence of the primary researcher and were valid. Although some of the symptoms in patients were ascribed to back problems, we did not attempt to differentiate or analyse this aspect, as all patients showed an improvement in symptoms in spite of the comorbidities. All parameters were analysed to test for significance of variation between pre-operative and post-operative measures.

Table 7.1 WOMAC Scores with individual parameters

Parameter	Pre op	SD	Post op	SD	p value
Pain	8.72	2.97	0.278	0	$3.6\ E^{-05}$
Stiffness	5.33	1.21	0.67	0.82	$9.2\ E^{-05}$
Function	35.77	7.96	2.17	2.92	$6.1\ E^{-05}$
Total	49.67	10.26	3.12	3.75	$1.5\ E^{-05}$

All patients were fully satisfied with the surgical procedure. The WOMAC scores improved significantly between the pre-operative and post-operative patient groups. The individual components of pain, stiffness, daily activities also showed significant improvement.

7.22 Modified Knee Society Score

Table 7.2 Modified Knee Society Score

Parameter	Pre op	SD	Post op	SD	p value
Pain	12.5	7.5	35	0	6.3 E^{-10}
Stairs	3.06	4.14	15	0	1.1 E^{-09}
ROM	14.22	1.73	15.67	0.76	6.2 E^{-05}
Stability	25	0	25	0	0
Total Knee Score	47.83	12.29	90.67	0.76	5.3 E^{-11}
F S Pain	17.78	4.05	40	0	6.1 E^{-10}
F S Stairs	21.67	7.46	40	0	1.3 E^{-08}
Total function	39.17	9.89	80	0	4.1 E^{-10}

The Modified Knee Society Score improved significantly between the pre-operative and the post-operative groups. The parameters of pain on walking and pain on stair climbing and the total score improved significantly. The range of movement improved by a mean of 11.5 degrees, this was statistically significant but less significant compared to the improvement in pain parameters and total score. The score for stability did not vary between the two groups as only stable knees were deemed suitable for medial unicompartmental knee replacements. The function scores for pain and stairs improved significantly. All patients had identical postoperative function scores which was a result of how the queries were made on the questionnaire.

7.3 Radiographic assessment

All patients had antero posterior, lateral and skyline views assessed prior to listing for surgery. All patients had isolated medial compartmental knee osteoarthritis. Alignment was assessed on long leg alignment views. The alignment was measured using the Hip Knee Ankle angle (HKA) and the location of intersection of the mechanical axis on the tibial plateau.

7.3.1 Reliability and agreement parameters for alignment measures

As the alignment views were assessed preoperatively and post operatively the measurement error on same radiographs assessed by the same assessor on two separate occasions, and measurement error on radiographs of the same limb taken on two separate occasions (preoperative and postoperative) was assessed as well. Intra class correlation coefficient (ICC) and standard error of measurement (SEM) was done for both radiographic measures used in this investigation, Hip Knee Ankle angle (HKA) and position of mechanical axis (MA) on the tibial plateau. The assessment for position of mechanical axis (MA) on the tibial plateau on the same radiograph at different points of time by the same assessor was extremely reliable (ICC =100). HKA angle measurement showed excellent reliability (ICC = 0.96) of measurement on the same radiograph. The HKA measurement on different radiographs for the same limb was less reliable (ICC = 0.79) but still considered excellent according to Fleiss (Fleiss 1979). The standard deviation for HKA measurement was 2.38 degrees and the Standard error of measurement (SEM) was 0.83 degrees.

7.32 Assessment of alignment

In the preoperative group the Hip knee Ankle (HKA) angle ranged from 169 degrees to 180 degrees (Mean=173.21 ± 2^{o}) and the postoperative HKA ranged from.172 degrees to 180 degrees (Mean= 175.99 ± 2.3 ^{o}). In the normal asymptomatic knees HKA ranged from 174 degrees to 180 degrees (Mean = 177.90 ± 1.98^{o}). Significantly, even though the postoperative alignment approached the mean alignment values for normal knees, they did not achieve equality.

In the preoperative patients the mechanical axis passed through central zone (n=0), zone 1(n=5), zone 2(n=12) and zone 3(n= 1). In the postoperative group the mechanical axis passed through central zone (n=4), zone 1(n=10), zone 2(n=4) and zone 3(n= 0).

The mean correction achieved in the HKA angle was 2.78 degrees (SD ± 1.32 ^{o}). On the basis of the HKA all eighteen knees underwent some correction. On the basis of location of mechanical axis five did not undergo noticeable correction on radiographic measurement. Amongst the knees that underwent correction, 3 degrees of correction corresponded to a shift of mechanical axis by more than one zone of the tibial plateau as described, and was the value of the standard deviation of the HKA angle as described previously. Although the alignment after correction approached the value for normal knees, it did not achieve normal values.

The correction of alignment in the fixed bearing unicompartmental knee replacements was 2.125 degrees as compared to 2 degrees for mobile bearing unicompartmental knee replacement. This difference was not statistically significant.

7.4 Gait Parameters

7.4.1 Time and Distance (Temporospatial) Parameters of Gait

The stride length and velocity were the distance parameters measured, while the cadence and double limb support time (DLST) were the time parameters recorded pre operatively and post operatively in all patients.

Table 7.3 Time and distance parameters for gait

Parameter	Cadence (steps/min)	DLST(s)	stride length (m)	Velocity (m/s)
Post-op value	109.24	0.08	1.10	1.15
Pre-op value	97.01	0.13	0.99	0.84
Difference	12.23	0.05	0.11	0.31
% Improvement	12.60%	64.12%	10.79%	37.45%
p value	0.08	0.001	0.174	0.01

Obtaining time and distance data requires that the markers on the test foot are visible through one complete gait cycle. In cases where two consecutive heel contacts of the test leg were not recorded, it was not possible to obtain these data. Time and distance parameters of gait are reported in Table 7.3. Time and distance data were available for sixteen knees. Paired t-tests confirmed that the replacement arthroplasty significantly improved the velocity, gait speed and double limb support time. Cadence improved by 12% but this only approached clinical significance. The 10% improvement in stride length did not reach statistical significance.

7.4.2 Reliability and Agreement measures for kinetic and kinematic parameters.

The measurement of joint kinetics was done on separate occasions, in the same patient before and after the operation. It was important to establish the reliability of measurements made on separate occasions as any differences would be attributed to the effect of replacement arthroplasty. The kinetic and kinematic variables measured in knees that were not replaced were used for this purpose. In order to reduce errors secondary to marker placement, placement of markers were done only by trained individuals in the gait laboratory (HE MK and JJ). On all occasions the placement accuracy was cross checked by HE, who is very experienced in the field of marker placements in gait analysis especially in paediatric assessments.

Table 7.4 Reliability and SEM for kinetic and kinematic parameters

	Parameter	ICC	SEM	95% CI	95% CI
Kinetics	Adduction Moment	0.99	0.001Nm/Kg (0.2%)	0.99	0.99
	Add.Imp	0.99	0.38Nm/Kg (2.1%)	0.99	1
	Flexion-Extension moment	0.87	0.07Nm/Kg (21%)	0.38	0.95
	Rotation Moment	0.76	0.01Nm/Kg (49%)	0.57	0.85
Kinematics	Flexion-Extension	0.98	1.5 degrees (7%)	0.96	0.98
	Varus- Valgus	0.66	3.26 degrees (83%)	0.5	0.77
	Rotation	0.87	2.27 degrees (18%)	-0.12	0.96

The reliability and agreement measurement revealed excellent reliability statistics for peak coronal plane kinetics namely, peak knee adduction moment (PKAM), Adduction impulse (Add Imp) and flexion – extension moment among kinetic parameters. Among kinematic parameters flexion – extension angle and rotation angle showed excellent reliability and agreement. The standard error of measurement in the unit of measurement of the individual parameter and the percentage variation to individual measurement is reported in the table above.

7.4.3 Knee Joint Moments

The Knee joint kinetic parameters assessed were those measured in coronal plane (Peak Knee Adduction and Angular adduction Impulse), sagittal plane (early and late stance extension and flexion moments) and transverse plane (internal and external rotation moments). The assessment of adduction moment was analysed further as it is the most extensively studied and reported measure of joint loading in literature of gait analysis in osteoarthritis.

7.4.3.1 Reliability of Measure of Adduction Moments on two separate occasions

The reliability of measurement was excellent (ICC= 0.99). The mean Knee adduction moment was plotted with standard deviations for the first and second measurements. The mean Peak Knee Adduction Moment and the Angular Adduction Impulse were recorded. The correlation between the pre operative and post operative measurement was assessed.

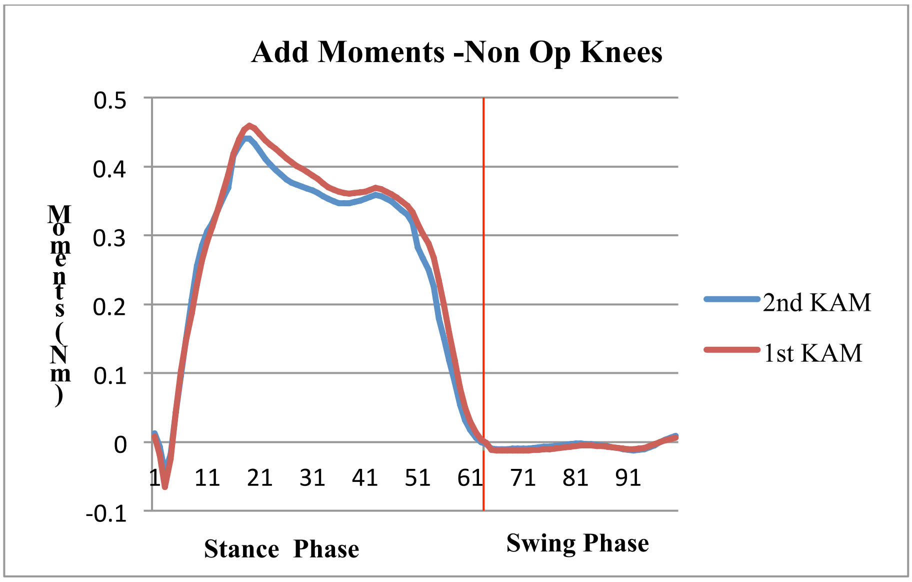
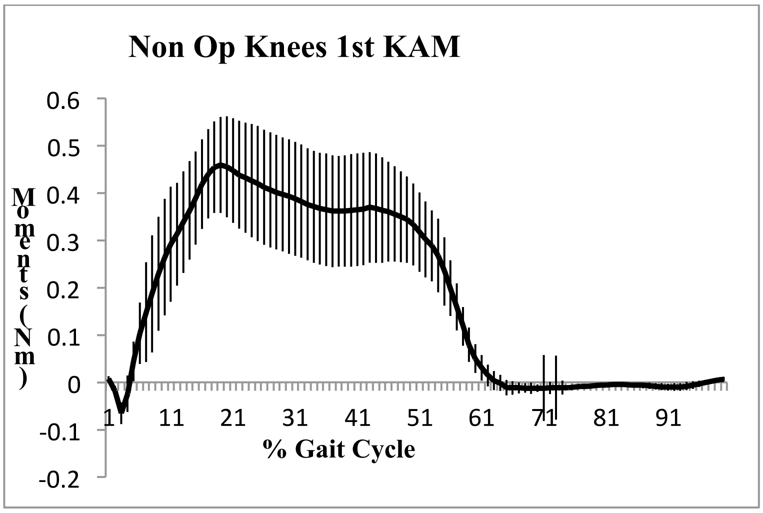


Figure 7.1 Knee Adduction Moment plots for Non operated knee on 2 separate occasions.



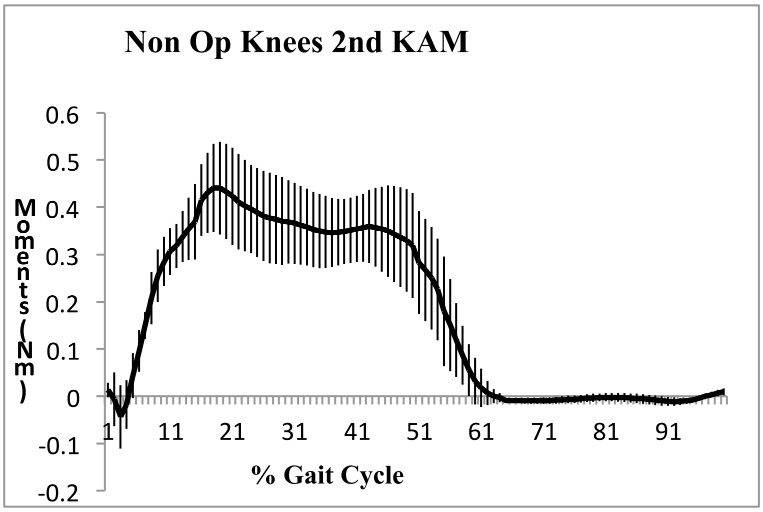


Figure 7.2 Adduction moments in Non operated knees (2 separate measures) with SD

Table 7.5 Coronal plane kinetics on 2 separate occasions on non operated knees.

	Mean PKAM	SD	Mean Add Imp
1st measurement	0.459	0.1	18.39
2nd measurement	0.44	0.98	17.43

The measurement of knee adduction moments was found to be reliable between two measurements. The correlation was measured (r=0.9975) and Standard Error of Measurement

(SEM) was 0.001Nm/kg (0.2%)

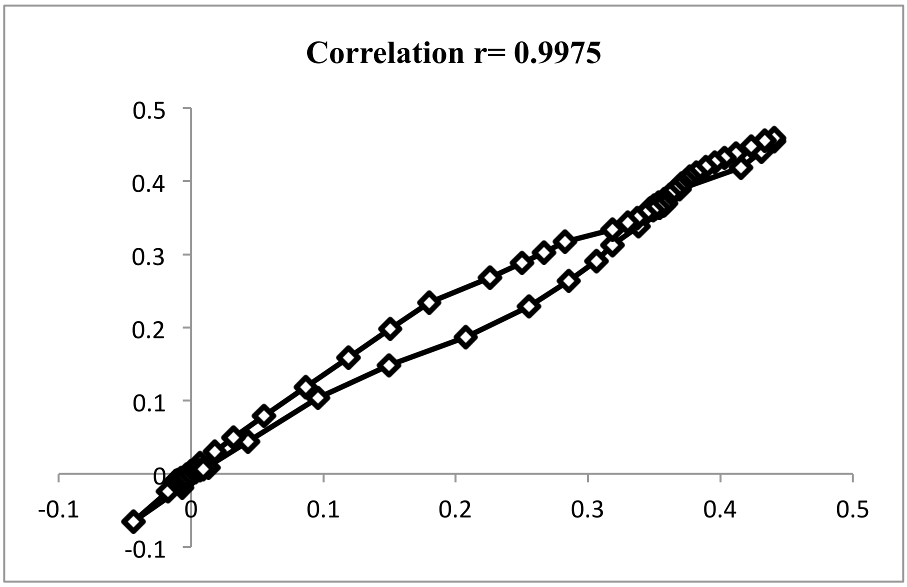


Figure 7.3 Correlation between two measurements.

7.5 Coronal plane kinetics in Medial Compartment Osteoarthritis of knees.

The preoperative coronal plane kinetic parameters of arthritic knees that underwent replacement arthroplasty were compared to nonarthritic asymptomatic knees in the same group of patients. The frontal plane kinetic outcome measures recorded were Peak knee Adduction Moment (PKAM) and Adduction Angular Impulse (Add Imp).

The arthritic knees were found to have higher Peak Knee Adduction moment and Adduction impulse when compared to the asymptomatic non arthritic knees.

Table 7.6 Coronal plane kinetics of Arthritic vs Non arthritic knees

Parameter	Arthritic knees	Non arthritic Knees
Add Imp	22.70±5.11 SD	17.11 ± 5.35 SD
PKAM	0.508±0.14 SD	0.42 ± 0.09 SD

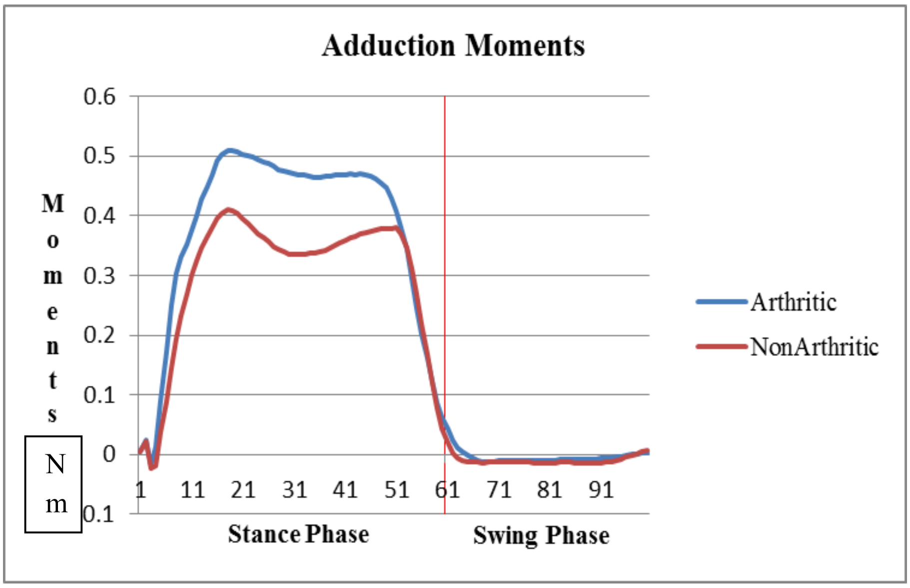


Figure 7.4 Adduction moment plot of Arthritic and Non arthritic knees.

The arthritic knees were found to have a greater PKAM and Add Imp, the difference was statistically significant. The pattern of the adduction moment curve does not show the typical double hump curve on the adduction moment plot in arthritic knees.

7.5.1 The Effect of replacement on Coronal plane kinetics

The alteration in coronal plane kinetics in the knees with unicompartmental knee osteoarthritis following replacement arthroplasty was analysed.

Table 7.7 Coronal plane kinetics in knees prior to and following replacement

Parameter	Pre op	Post op	SD	p value
Add Imp	22.70	17.67	5.11	0.004
PKAM	0.51	0.41	0.14	0.011

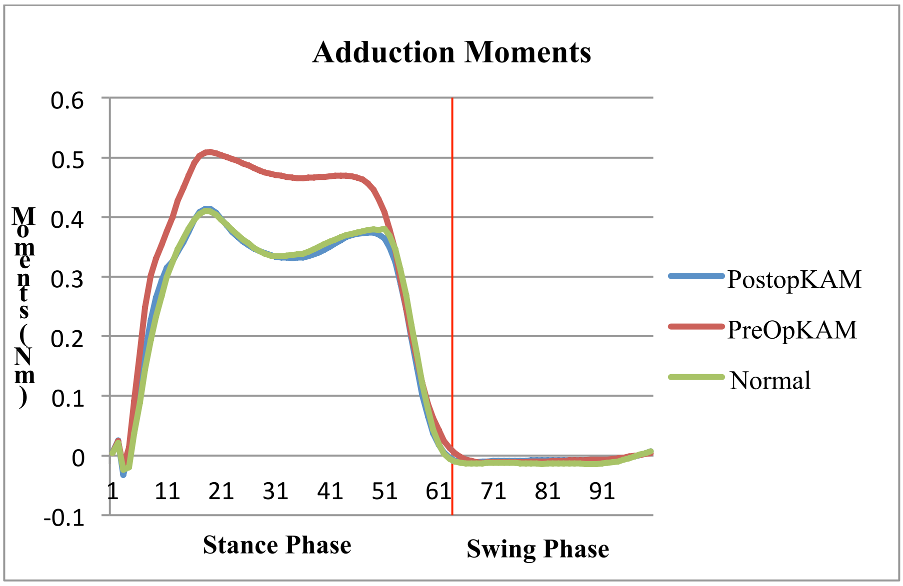


Figure 7.5 Adduction Moments plot for pre operative and post operative measurements for replaced knees

The knees that underwent medial unicompartmental knee replacement demonstrated statistically significant reduction in the Peak Knee Adduction Moment and Adduction Impulse. The improvement in Add Imp was greater when compared to PKAM as it is a better and more representative measure. The pattern of the adduction moment curve assumed a more typical double hump pattern following unicompartmental knee replacement. Incidentally the adduction moment curve in the postoperative group was almost identical to the adduction moment curve recorded in the asymptomatic knees (Normal knees).

7.5.2 Effect of Alignment on coronal plane Kinetics

The replaced knees were divided into 3 groups depending on the correction of alignment. The alignment was measured on long leg alignment views. The 'High correction group' showed an increase in HKA angle of greater than 3 degrees. This group showed a definite movement of the mechanical axis through more than the width of at least one zone on the tibial plateau. The 'Low correction group' showed correction in HKA angle of less than 3 degrees, which corresponded to variation less than the width of one zone of the tibial plateau. The patients were divided only into the above two groups on the basis of Hip Knee Ankle (HKA) angle. But on the basis of the location of mechanical axis the low correction group had a further subset the ‘Uncorrected group’ with knees that did not show any difference in postoperative alignment from their preoperative alignment.

7.5.2.1 The Effect of correction of alignment on coronal plane kinetics

The effect of alteration of alignment on coronal plane kinetics of the knee was analysed.

Table 7.8 Effect of correction of alignment on coronal plane kinetics

Parameter	Pre op	Post op	SD	p value
Add Imp	23.66	17.67	3.73	0.0000
PKAM	0.53	0.42	0.10	0.007

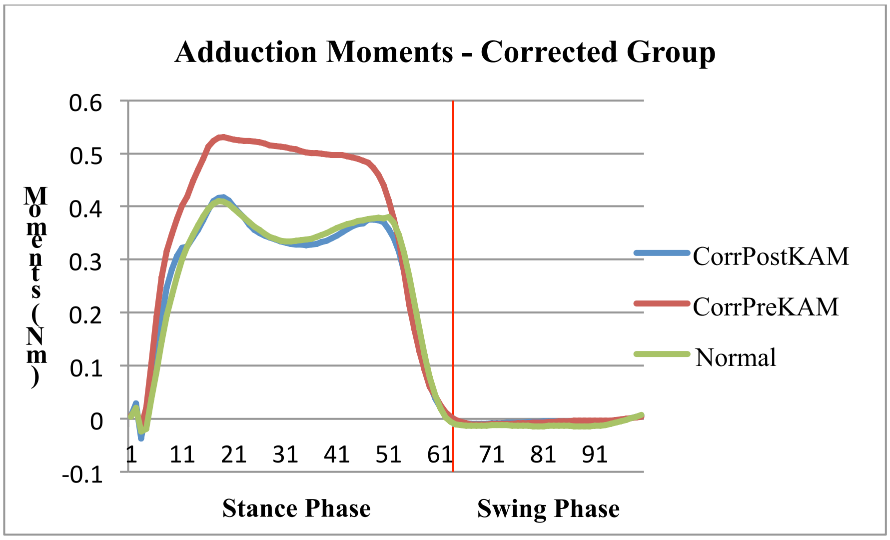


Figure 7.6 Adduction Moment plot for preoperative and postoperative values for replaced knees that showed correction of alignment (HKA angle).

Peak Knee adduction moments (PKAM) and adduction Impulse (Add Imp) showed statistically significant reduction in knees that underwent correction of alignment at the time of unicompartmental knee replacement arthroplasty. There was a greater reduction in the peak knee adduction moment (5%) and adduction impulse (20%) in those knees whose alignment was corrected.

Replacement arthroplasty of the medial compartment of the knee restored the coronal plane kinetics to nearly identical levels as kinetics in asymptomatic non arthritic knees from the same patient group.

In order to further analyse the effect of correction of alignment on the frontal plane kinetic parameters, a comparison between groups where a low correction (less than 3 degrees) and a high correction (greater than 3 degrees) was achieved was done.

7.5.2.2 Comparative analysis between the 'low correction' group and 'high correction' group

Table 7.9 Effect of alignment on Coronal plane Kinetics

Group	Parameter	Pre op	Post op	SD
Low Correction	Add Imp	21.97	18.26	2.15
Low Correction	PKAM	0.51	0.42	0.21
High Correction	Add Imp	25.20	16.30	4.66
High Correction	PKAM	0.55	0.40	0.14

The reduction in the adduction impulse (Δ Add Imp) and Peak Knee adduction moment (Δ PKAM) was significant ($p < 0.05$) when there was a correction in alignment more than three degrees or when the mechanical axis is moved more than the width of a zone on the tibial plateau.

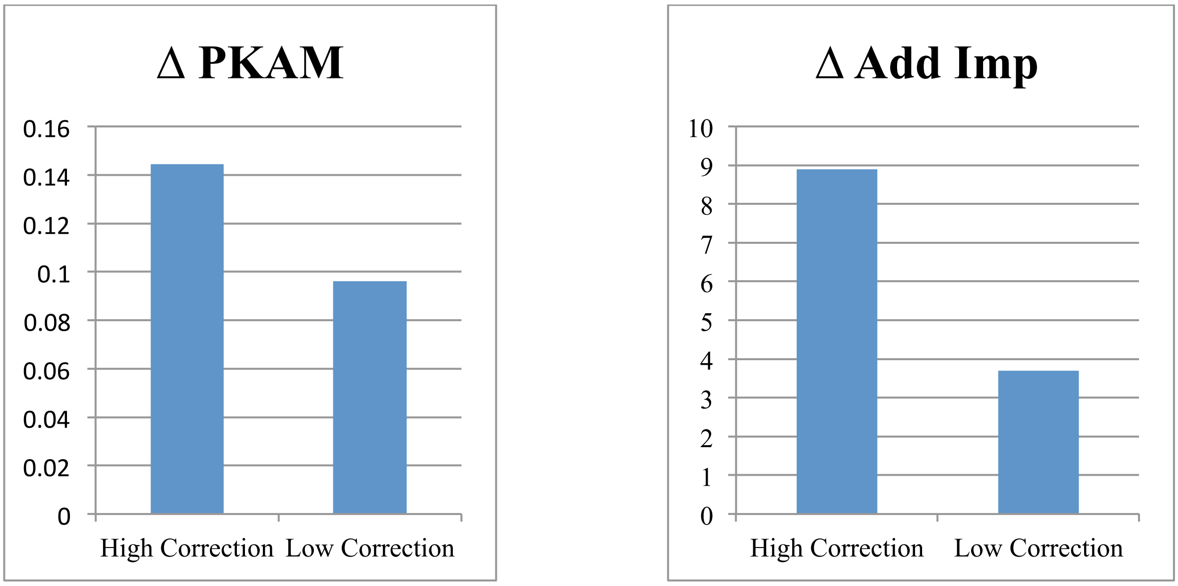


Figure 7.7 Plots for difference between Preoperative and Postoperative values for Peak Knee Adduction Moment (Δ PKAM) and Adduction Impulse (Δ Add Imp).

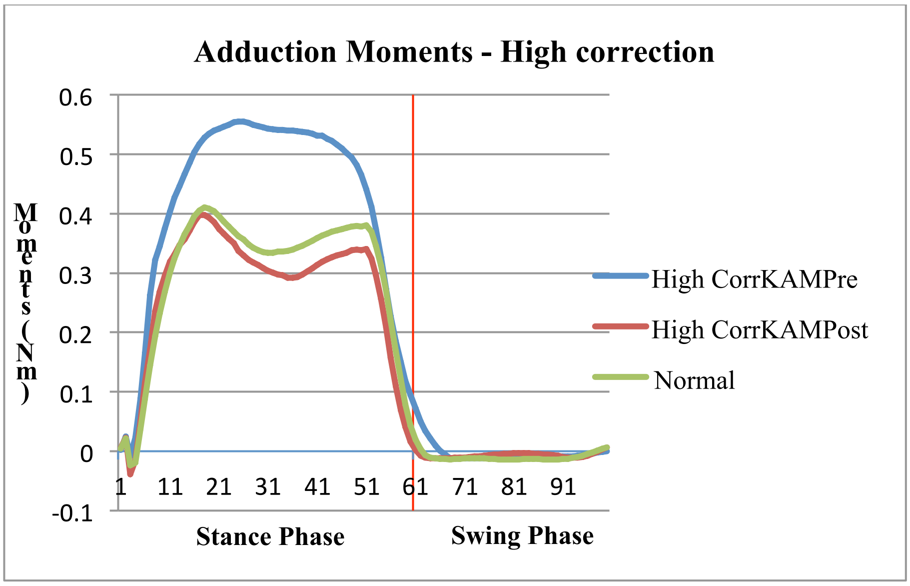


Figure 7.8 Adduction Moments in the group of knees where a high correction (>3 degrees) was achieved.

In knees where the alignment was significantly corrected (mean correction = 4.33 degrees) the coronal plane loading improved through the entire stance phase to levels lower than those for the non arthritic asymptomatic knees. The reduction in adduction moment was highly significant ($p=0.00004$)

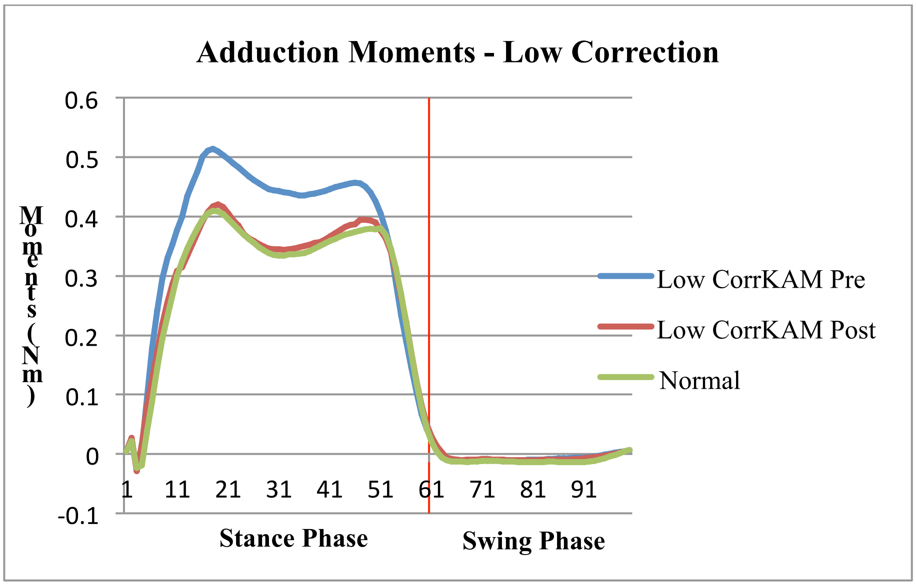


Figure 7.9 Adduction Moments in knees where the correction was < 3 degrees

The adduction moment decreased even in the knees where the correction of alignment was less than 3 degrees (p=0.006). The reduction was not as significant as in the knees where the correction exceeded 3 degrees (p=0.00004).

7.5.2.3 The effect of replacement arthroplasty on knees without correction of alignment ('Uncorrected group').

Table 7.10 Coronal plane kinetics in knees where alignment did not change

Parameter	Pre op	Post op	SD	p value
Add Imp	22.15252	19.14187	4.21	0.004
PKAM	0.499694	0.397445	0.2	0.014

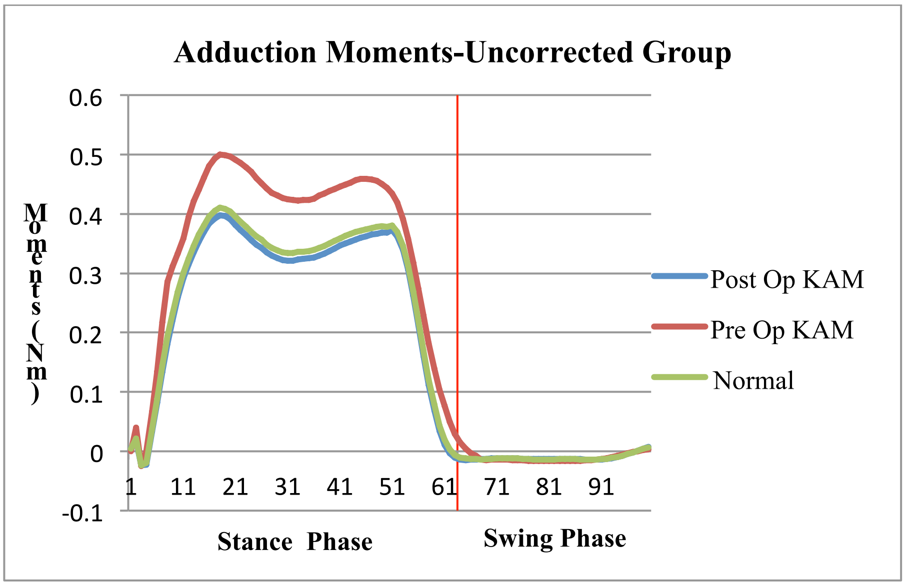


Figure 7.10 Adduction moment plot for knees that showed no correction of alignment on replacement (MA)

The group of knees that did not show any alteration in alignment based on the location of the mechanical axis on the tibial plateau demonstrated a statistically significant reduction in the Peak Knee adduction moment and Adduction moment impulse in the knees post operatively.

7.6 The effect of replacement on Sagittal plane Kinetics

The average peak knee flexion moment in early stance and late stance occurred at approximately the same time in the pre and post operative groups. Similar observations were found for the two extension moments in early and late stance phases.

Table 7.11 Preoperative and postoperative sagittal plane kinetics after medial unicompartmental knee replacements.

Parameter	Pre op	Post op	p value
Early stance Extension Moment	0.14	0.23	0.05
Early stance Flexion Moment	0.25	0.26	0.87
Late stance Extension moment	0.04	0.07	0.57
late stance Flexion moment	0.13	0.22	0.26

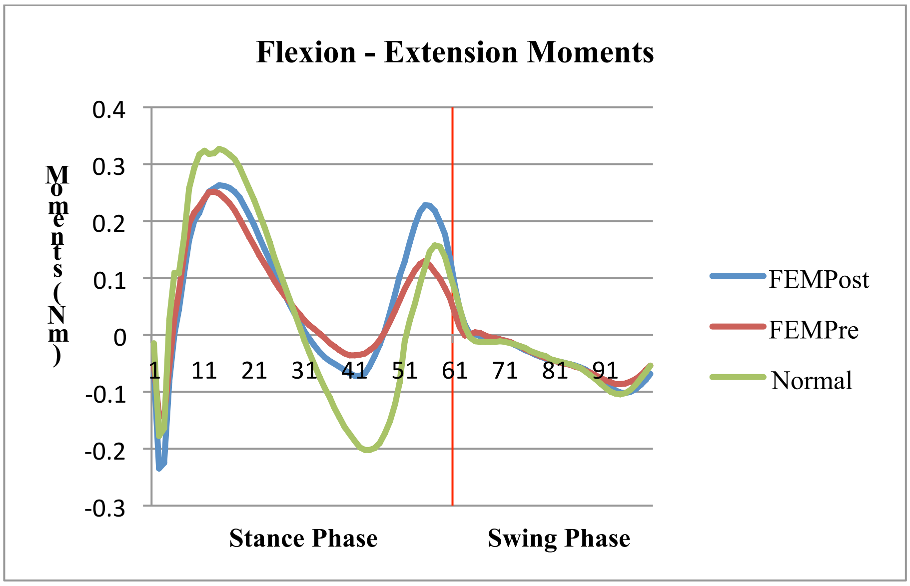


Figure 7.11 Flexion Extension Moment Plot for Preoperative and Postoperative groups.

The early stance extension moment was the only statistically significant factor that improved following medial unicompartmental knee replacements, to the extent that it improved beyond the early stance extension moment for nonarthritic knees. Although there was an improvement in early stance flexion moment and late stance extension moment between the preoperative and post operative measurements of the replaced knees, these did not reach statistical significance. The late stance flexion moment was higher than the values for preoperative measurement and the normal knees, but again this did not reach statistical significance. The early stance flexion and late stance extension were lower in the arthritic knees when compared to normal knees.

7.7 The effect of replacement on transverse plane kinetics

The mean peak internal and external rotation moments occurred at similar points of the stance phase of the curve in all three groups. The peak rotation moments in both directions were recorded and compared between the preoperative and postoperative group of knees. The differences were calculated.

Table 7.12 Preoperative and postoperative Peak external and internal rotation moments following unicompartmental knee replacements

Parameter	Pre op	Post op	SD	p value
External Rotation Moment	0.03	0.02	0.02	0.78
Internal Rotation Moment	0.05	0.06	0.02	0.92

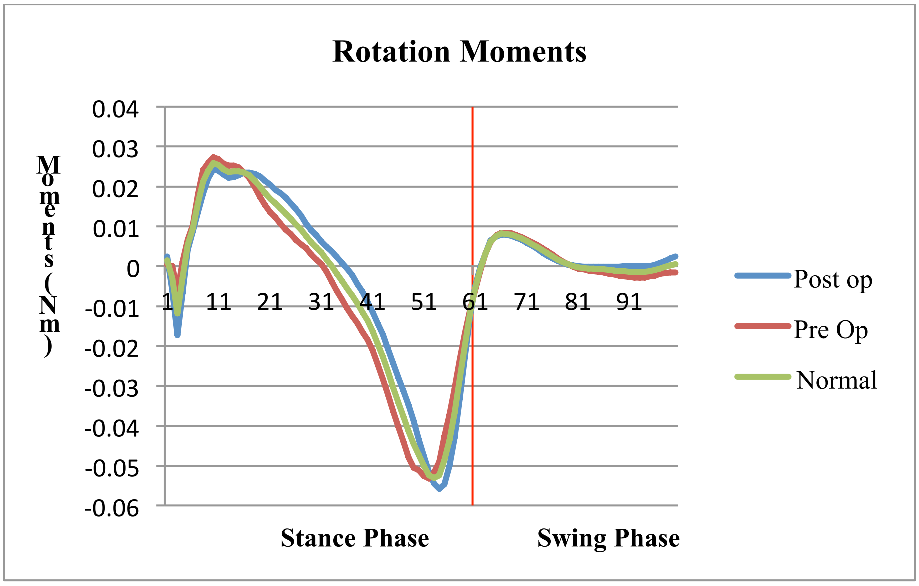


Figure 7.12 Transverse plane moments for preoperative and Postoperative groups.

There was a small increase in the external rotation moment and the internal rotation moment. Neither of these changes was statistically significant. The rotation moments of the knees prior to and subsequent to replacement were nearly identical to the the nonarthritic knees.

7.8 Knee Joint Kinematics

The kinematic parameters analysed were sagittal plane parameters (knee flexion –extension), coronal plane parameters (Knee varus- valgus) and transverse plane parameters (internal-external rotations)

7.8.1 The effect of replacement on sagittal plane kinematics of the knee (flexion extension)

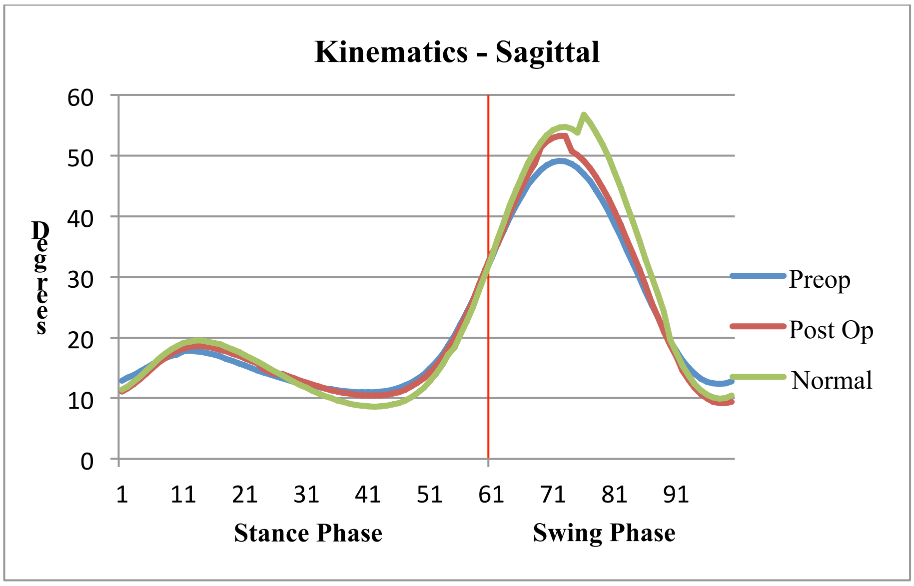


Figure 7.13 Sagittal plane Kinematics (Flexion- Extension)

The flexion – extension range in stance did not show significant difference between preoperative and postoperative values and were nearly identical. The flexion range in swing improved following the replacement surgery, nearly to the normal range but this difference did not reach statistical significance.

7.8.2 The Effect of Replacement on Coronal plane kinematics

Table 7.13 Mean values for Coronal plane kinematics

Parameter	Normal	Pre operative	post operative
Peak adduction	2.42	7.09	5.31
Mean adduction	1.77	6.03	1.45
Adduction Excursion	2.61	3.64	5.62

The mean adduction angle at foot contact was highest in the preoperative group. The mean adduction angle reduced in postoperative knees to values similar to normal knees.

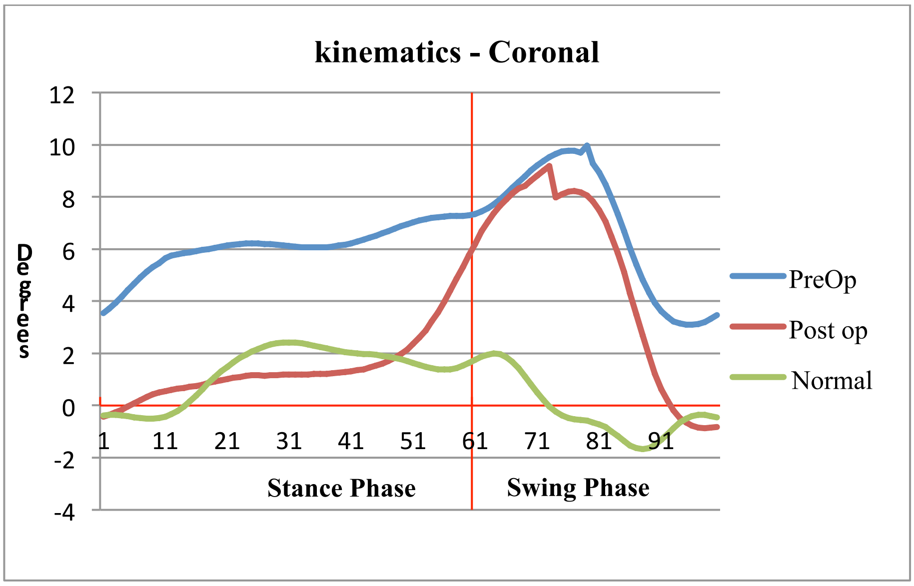


Figure 7.14 Adduction – Abduction (Varus-Valgus) angles

The valgus- varus range in stance phase in the post operative knees improved to levels similar to the normal knees. The improvement in stance phase was statistically significant, but this finding needs to be viewed in the background of coronal plane kinematic measurements being unreliable.

The effect of correction of alignment on coronal plane kinematics

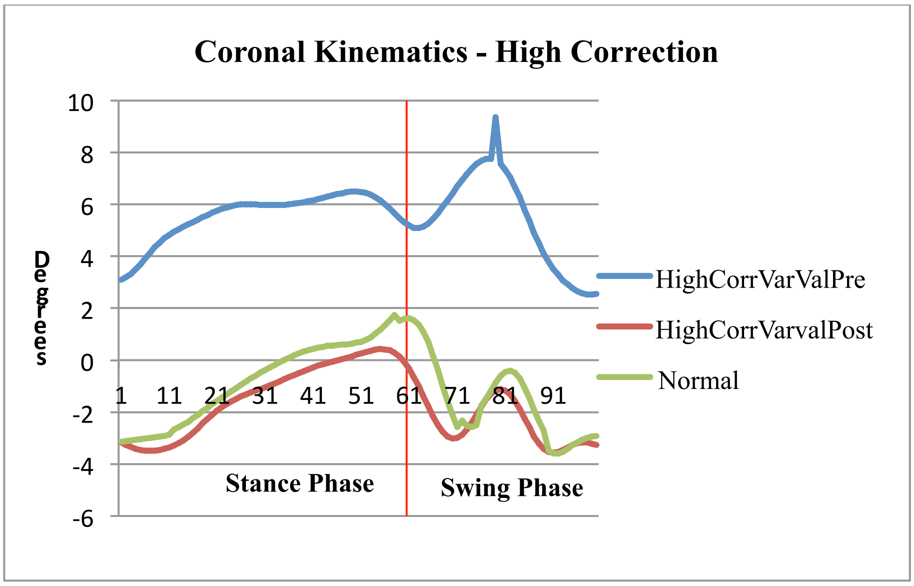


Figure 7.15 Adduction- Abduction (Varus-Valgus) angles in the High Correction group.

The varus position at the initial stance position improved in the patients following replacement arthroplasty. The knees in which a correction in static alignment of greater than 3 degrees was achieved showed a correction of Mean adduction angle of 6.94 degrees.

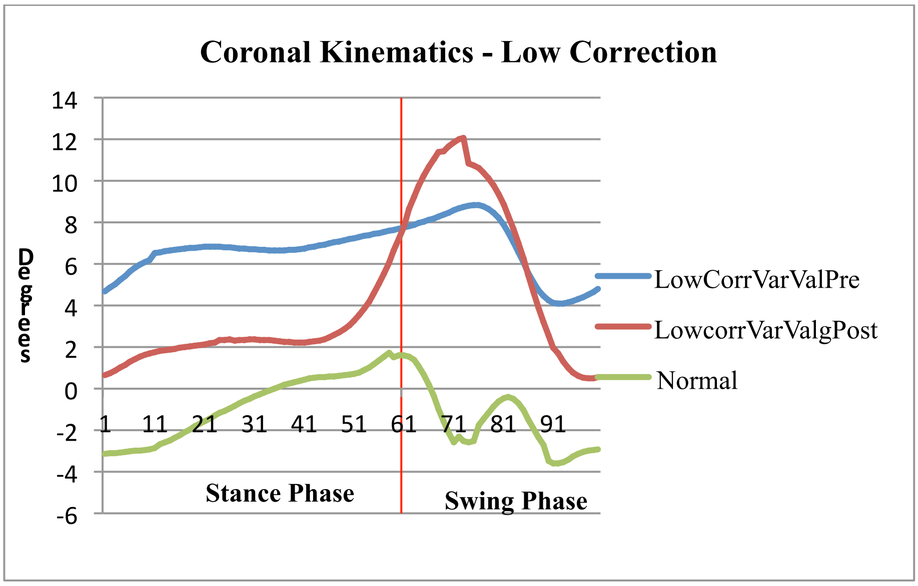


Figure 7.16 The varus valgus (adduction-abduction) angles in low correction group

In the low correction group the correction of Mean adduction angle showed a reduction of 4.124 degrees in the post operative knees.

7.8.3 The effect of replacement on Transverse plane Kinematics

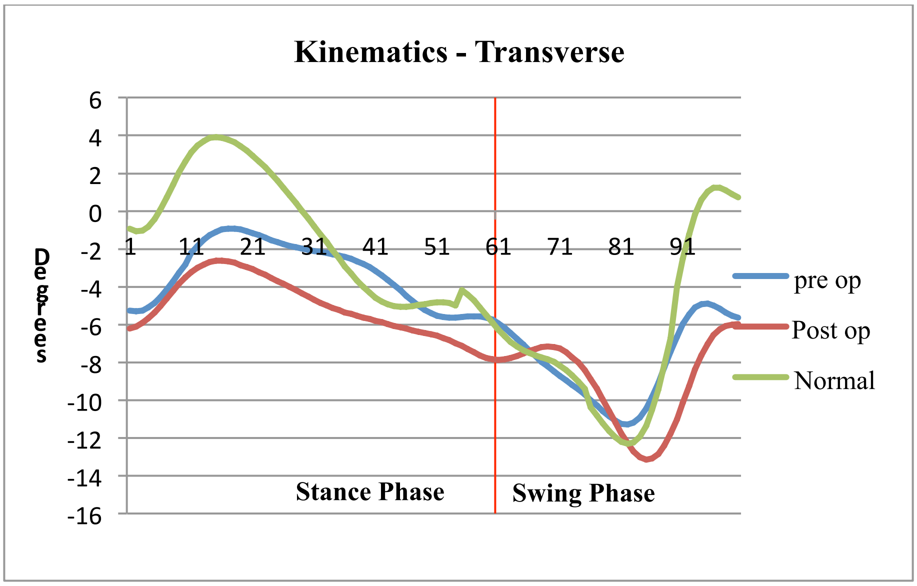


Figure 7.17 Rotation angles (Internal –positive) of the knees

The arthritic knees were in greater external rotation than the normal knees in early stance phase, possibly as part of a compensatory mechanism to decrease medial compartmental loading. In the replaced group, the knees were in greater external rotation than the normal knees and this continued to increase during the swing phase. The difference between the preoperative and postoperative measurements was not statistically significant.

7.9 Alteration of alignment Predicts PKAM and Add Imp – Regression Analysis

It is clear from the results of paired t tests that alignment has an effect on both the coronal plane kinetic parameters. Regression analysis was done to assess if correction of alignment was predictive of the improvement in PKAM and Add Imp. A single regression analysis was carried out to evaluate the effect of Hip knee Ankle angle (HKA) and Mean Adduction Angle (MAA) on the preoperative an postoperative PKAM and Add Imp.

Table 7.14 Peak Knee Adduction Moment

	Parameter	B	Std. Error	95% CI Lower Bound	95%CI Upper Bound	p value
Pre Op Knees	HKA	-0.13	0.19	-0.53	0.28	0.51
	MAA	0.27	0.13	0	0.54	0.005
Post Op Knees	HKA	-0.024	0.013	-0.052	0.004	0.09
	MAA	0.004	0.009	-0.015	0.023	0.668

Table 7.15 Adduction Impulse

	Parameter	B	Std. Error	95% CI Lower Bound	95%CI Upper Bound	p value
Pre Op Knees	HKA	-0.472	0.753	-2.06	1.12	0.51
	MAA	1.374	0.448	0.42	2.32	0.007
Post Op Knees	HKA	-1.47	0.562	-2.662	-0.279	0.019
	MAA	0.49	0.28	-0.104	1.084	0.099

The Mean Adduction Angle was a significant and better predictor of PKAM and Adduction Impulse than HKA in preoperative knees, while in post operative knees the HKA was a significant predictor of PKAM and Add impulse. This indicates that both MAA and HKA are adequate measures of alignment.

A further analysis was carried out to evaluate the effect of correction of HKA on ΔPKAM and ΔAdd Imp. As the values of ΔPKAM and ΔAdd Imp for individual knees were quite variable for similar angular corrections of HKA, a percentage variation of the PKAM and Add Imp was used.

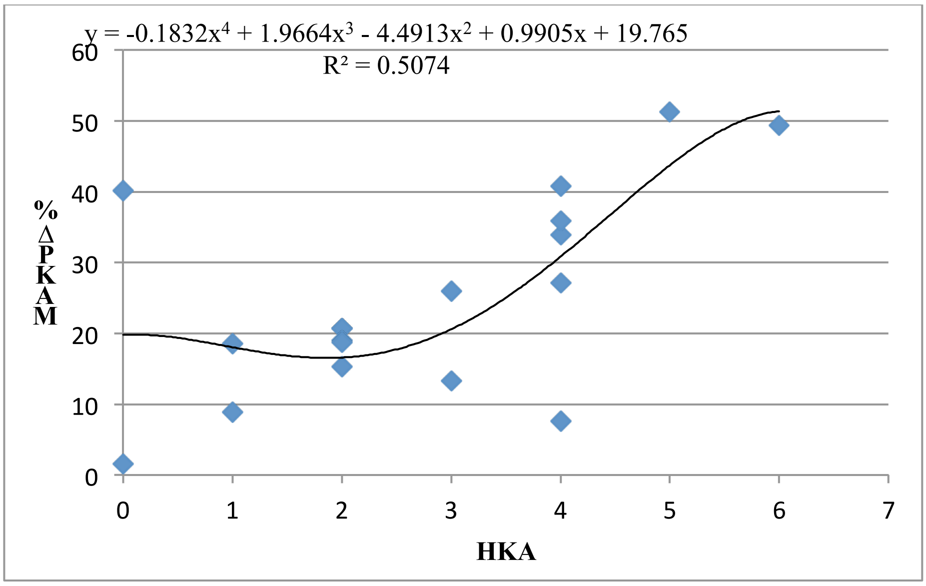


Figure 7.18 Regression line for relationship of ΔPKAM with HKA

There were 2 values which did not fit the regression line and were outliers.

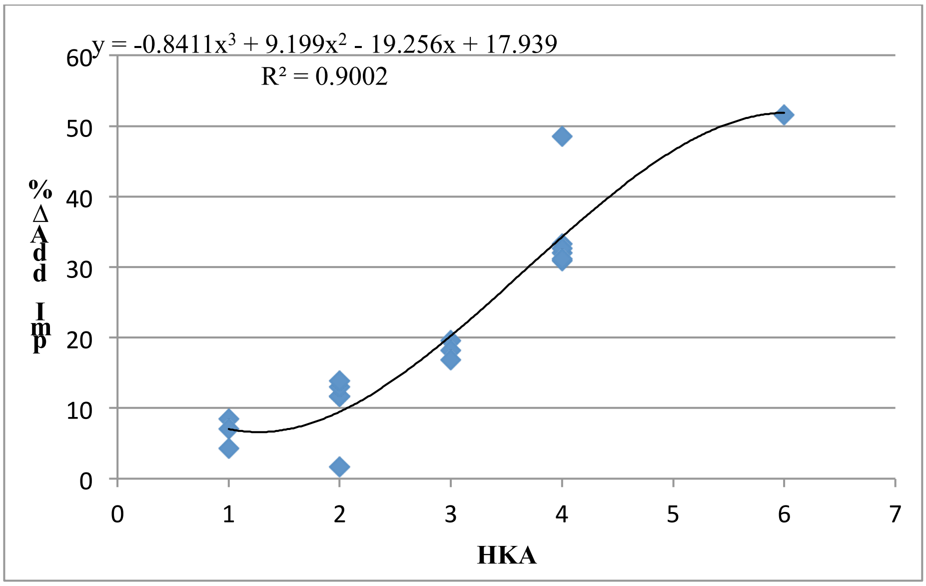


Figure 7.19 Regression line for relationship of %ΔAdd. Imp with HKA

The analysis revealed that only 50% variation in the ΔPKAM value could be attributed to alterations in HKA while 90% of variation in ΔAdd Imp was secondary to corrections in HKA angle. The regression analysis revealed that for every one degree of correction HKA angle the adduction impulse reduced by 7% and for every 3 degrees of correction which was the median correction in the series, there was a reduction in the adduction impulse by 21%.

7.91 Multiple regression analysis

A multiple regression analysis was performed to analyse the effect of Hip Knee Ankle angle (HKA) and Mean Adduction Angle (MAA) on adduction impulse. Both values, it should be remembered are measures of alignment at the knee. The two variables accounted for 91% of the variation in the adduction impulse.

Table 7.16 Output for multiple regression analysis for HKA and MAA on Add Imp

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-11.384	3.0236	-3.765	0.0018	-17.829	-4.9392
HKA	10.0984	0.8286	12.186	3.5E-09	8.33221	11.8646
MAA	-0.7445	0.2607	-2.854	0.0120	-1.3003	-0.1887

Although both variables were significant predictors for reduction in adduction impulse, the HKA was found to be a far more significant predictor of variation in adduction impulse compared to MAA.

Multiple regression analysis was done to assess the effect of HKA and MAA on PKAM

Table 7.17 Output for multiple regression analysis for HKA & MAA on PKAM

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.01238	7.71174	-0.00161	0.998741	-16.5524	16.52765
HKA	6.213977	2.068024	3.004789	0.009461	1.778506	10.64945
MAA	-1.36438	0.645138	-2.11486	0.052859	-2.74806	0.019308

Both alignment measures namely HKA and MAA were significant predictors of variation in the peak knee adduction moment but as with the adduction impulse, HKA was found to be a better predictor.

7.10 Summary of results of study 2

Reliability of radiographic and gait parameters; All radiographic and gait kinetic and kinematic parameters showed excellent reliability as per Fleiss classification of ICC, except coronal plane kinematics (ICC=0.66). The coronal plane kinematics was still considered useful as it was greater than 0.6.

Clinical scores; All components and total domains of WOMAC score and Knee Society Score showed statistically significant improvement following unicompartmental knee replacement.

Time and distance parameters; All parameters assessed improved following unicompartmental knee replacement, velocity and Double limb support time were statistically significant.

Variation in kinetic parameters following unicompartmental knee replacements; The kinetic parameters (PKAM & Add Imp) tested in the coronal plane improved to achieve statistical significance. The only kinetic parameter in sagittal plane that improved to achieve statistical significance was early stance extension moment. None of the other kinetic parameters in the sagittal plane (late extension moment and early and late flexion moments) varied enough to achieve statistical significance. None of the transverse plane kinetic parameter variations achieved statistical significance.

Variation in kinematic parameters following unicompartmental knee replacements; There was no statistically significant variation in any of the kinematic parameters.

The effect of alignment on coronal plane kinetics; Reductions in ΔPKAM and ΔAdd Imp were larger in knees that underwent greater (>3 degrees) of correction of alignment. This variation was statistically significant.

Correction of alignment as a predictor of medial compartment loading; Variations in measures of static alignment (HKA) were found to be significant predictors for percentage variation of ΔPKAM and ΔAdd Imp (%ΔPKAM and %ΔAdd Imp). The ΔHKA and ΔMAA were significant predictors of %ΔAdd Imp. The ΔHKA was a far more significant predictor of improvement in adduction impulse than ΔMAA. The relationship on regression analysis was revealed to be a 3rd order polynomial relationship. The ΔHKA was a more reliable predictor of adduction impulse (r^2 =0.90) than of PKAM (r^2 =0.50).For every degree of correction in alignment (ΔHKA), the %ΔAdd Imp improved by 7%. This equated to 22% for the median correction (3 degrees) and 44% for the highest correction achieved.

Chapter 8

Discussion

8.1 Demographics

The patients analysed in our study were predominantly male. The mean age of 65 years compares favourably to reports from other authors who have reported on the survivorship of unicompartmental knee replacements (Heck 1993, Cartier 1996, Berger 1999, Argensen 2002, Naudie 2004, Steele 2006, John 2008). All patients had medial unicompartmental knee replacements, following intraoperative assessment at the time of surgery.

8.2 Clinical Scoring Outcomes

The WOMAC scores improved in all the patients assessed as part of this investigation. Improvement in WOMAC scores have been reported by various authors following unicompartmental knee replacement (Naudie 2004, Whittaker 2010, Lyons 2012). We found statistically significant improvements in all the domains of the score including, pain, stiffness, function and total scores. Although papers on unicompartmental knee replacements have reported higher functional scores when compared to total knee replacements, the change in the total scores and the individual domains have not been significantly different between unicompartmental knee replacements and total knee replacements (Lyons 2012). Patients undergoing unicompartmental knee replacements tend to be younger which will tend to give them a better score preoperatively and postoperatively. The total number of patients in this study was small compared to other reports but improvement in clinical scores was not the main focus of this investigation.

The WOMAC score is an excellent patient reported outcome score. The knee society scores provide additional information on alignment, instability, deformity and lag apart from function and pain. The knee society score have been reported to improve following unicompartmental knee replacements by other authors (Naudie 2004, Lyons 2012). The knee society score provides a differential between function scores and knee scores, with function scores indicating the general condition of the patient and the knee scores indicating the condition of the knee. In one report comparing unicompartmental knee replacement patients and total knee replacement patients it was found that the knee score favoured total knee replacement patients while the function scores favoured the unicompartmental knee replacement patients (Lyons 2012). This phenomenon is intuitive as the scoring system penalises malalignment. The total knee replacements are more likely to be well aligned as the aim of the operation to achieve a perfectly aligned knee, while this is not the primary concern in unicompartmental knee replacements, which is a resurfacing procedure of one compartment. All patients in our investigation demonstrated significant improvement in the separate domains for knee scores and function scores. The postoperative function scores for all patients were identical. This is partly due to how function scores are calculated and weightage given to individual questions. Some of the deficiencies in the knee society scores have been addressed in the latest revised knee society score (Scuderi 2012)

8.3 Radiographic Outcomes

8.3.1 Reliability of alignment measurements

The measurement of HKA angle and location of mechanical axis is very reliable between measures by the same evaluator on the same radiograph. The location of mechanical axis showed 100% reliability between measures (ICC=100) this was comparable to reports on reliability of mechanical axis measurements on digital radiographs by Marx et al (Marx 2011). The HKA angle measurement was very reliable (ICC=0.96) which was comparable to other reports of intra class coefficients assessing HKA angles in long leg alignment radiographs (Rauh 2007, Sled 2007, Marx 2011). On the radiographs of the same limb made at different points of time the ICC was 0.79 which would still be classed as excellent. The reliability of measures on radiographs for measuring alignment parameters like HKA and MA was found to be excellent for the purpose of the investigation.

8.3.2 Alignment following medial unicompartmental knee replacement

In medial unicompartmental knee replacement surgery, the ideal post-operative limb alignment is not clear, with some surgeons feeling that unicompartmental knee replacement is primarily a ligament balancing procedure. This would imply that post-operative limb alignment after a medial unicompartmental knee replacement is variable, as the final alignment depends on the original preoperative alignment. It is believed that the object of surgery is to simply replace the worn intra-articular joint surface, restoring the mechanical axis of the lower limb to its physiological position before the onset of degenerative changes and subsequent progression of the varus alignment in the case of medial unicompartmental osteoarthritis of the knee (Cartier 1977). In this investigation the surgeons did not attempt to achieve correction at the time of surgery with ligament releases. This philosophy of under correction in unicompartmental knee replacement surgery is a big contrast to the traditional view of attempting to achieve neutral mechanical axis alignment while performing a total knee replacement. With the gaining popularity of the use of kinematic alignment in total knee replacement, the neutral mechanical axis alignment is not always considered a goal anymore even in total knee replacement surgery. Thus in unicompartmental knee replacements a patient-specific physiological alignment is often achieved by under correcting the angular deformity while protecting the healthy opposite compartment. Studies of lower limb alignment in the normal population have shown the tibio femoral axis to be slightly varus and this supports the philosophy of slightly under correcting the deformity in varus knees (Hsu 1990). Some authors advocate restoring the mechanical axis to pass through the centre of the knee joint (Emerson 2002). However, overcorrection of the varus deformity is thought to accelerate degenerative change in the lateral compartment (Murray 1998). But progression of arthritis in the lateral compartment is not always secondary to overcorrection of mechanical axis (Emerson 2008).

Although authors have reported preoperative planning to achieve precise post-operative alignment (Keene G 2005), no specific angular alignment or magnitude of correction was aimed for at the operation in this series. In the present series, the surgeon placed the prosthesis in such alignment as dictated by the soft tissue tension of the knee. The mean correction of the HKA angle achieved was 2.78 degrees (SD 1.32 degrees). This is similar to the planned correction reported in Keene's series (2.38 degrees) which was achieved as per the plan made preoperatively. The range of correction achieved in this group was from 0 degrees to 6 degrees. This was very similar to other reported series that have measured alignment parameters after unicompartmental knee replacements (Keene G 2005, John J 2009). The postoperative HKA ranged from 171 degrees to 180 degrees (Mean= 175.84), which was very similar to the alignment of the lower limbs reported for the normal population (Hsu 1990). The post-operative alignment according to the location of the mechanical axis method revealed that none of the knees had the mechanical axis pass outside the edge of the tibial plateau (zone 3). The location of mechanical axis in zone 3 is not considered ideal as this can significantly increase the loading on the medial uni compartmental knee replacement which in turn could affect the survivorship of the prosthesis (Kennedy 1987). None of the knees underwent significant overcorrection such that the mechanical axis passed through the unaffected lateral compartment which could hasten degeneration of the unaffected compartment. The majority of the knees demonstrated that the mechanical axis passed through zones 1 and 2 revealing the successful under correction of alignment. It has been reported that knees with mechanical axis medial to the medial edge of proximal tibial plateau (HKA angle less than 170 degrees) are more likely to increase wear of polyethylene inserts, which in turn can lead to earlier revision (Kennedy 1987).

8.4 Outcomes of gait analysis

This section will consider the biomechanical outcomes of the study that were collected in the gait analysis laboratory prior to and after the medial unicompartmental knee replacement surgery. The instrumented gait assessment was performed using standard motion analysis techniques. These techniques make the assumption that retro reflective surface markers represent bony anatomical points. These bony points are then used to produce coordinate frames with respective bones embedded in it. The gait analysis model used was from the standard Davis marker set. The Davis marker model is one of the most commonly used models in gait analysis. Numerous reports on gait studies have used this model and this model is used by the ELICLINIC software used in this study.

The Davis model has had criticisms especially when used in the patients requiring total joint arthroplasty (Baker 1999). The patients requiring total knee replacement tend to be older patients and the use of trochanteric marker has been considered to be intrusive resulting in patients not being relaxed when walking in the gait laboratory. The tracking of this marker can occasionally be difficult due to interference from clothing (Attfield 2010). Awareness of these problems helped us in this study. We did not have problems in tracking the marker by cameras, nor was it a significant inconvenience to the patients. The second criticism of the Davis marker protocol is with the axes and the centre of rotation of the knee. The model derives the centre of the knee from the midpoint of the measurement of the inter epicondylar distance entered into the software program. This is open to measurement error. More over the flexion extension axis is inferred from the accurate and repeatable placement of the lateral epicondyle marker. Different modifications have been used to measure centre of the knee more accurately, like the knee alignment jig and alignment of thigh wand marker with mirror (Attfield 2010). The accurate estimation of the knee centre can be a valid issue when comparing absolute values between population groups. This was not an issue in our study as the focus was on comparing the same patients prior to and after the replacement arthroplasty.

This investigation concentrated on differences in the individual variables, rather than on its absolute value, hence the technical details of whether the centre of knee calculation was accurate for the individual knee becomes irrelevant as long as measures were reproducible.
As the study intended to analyse the loading pattern in the knee following medial unicompartmental knee replacement, the measurement of coronal plane and sagittal kinetics was compared between two measurements on the unaffected, asymptomatic non arthritic knees from the same patient group.

The gait data was collected at a frequency of 100Hz. This acquisition speed is consistent with other studies of OA knees and TKR surgery. Previous acquisition speeds used have been 60 Hz (Chassin 1996), 100Hz (Fuchs 2002) and 240Hz (Saari 2005), 50 Hz (Deluzio 2007). These different ranges of acquisition speeds have been reported to be satisfactory for the purposes of investigating replacement arthroplasties in osteoarthritic populations. The frequency of data capture used in this study was considered to be sufficient to ensure that key data was not missed.

Traditional gait analysis computes both kinematic and kinetic parameters. The kinematic parameters consider the rotation of joints, and kinetic parameters consider the computation of moments and power from force plate data. All twenty two patients (twenty five knees) successfully completed gait analysis prior to surgery.

The walking velocity, mean step length, cadence and stance phase were recorded in order to evaluate walking. These parameters relate to ambulatory ability rather than knee function alone, but as the study compared these features nine months apart, factors other than the knee were unlikely to have changed significantly. Each participant was specifically asked prior to the follow –up gait analysis, if they had any problem that could potentially affect gait. One of the patients had his postoperative gait analysis postponed by four months to allow painful achilles tendinosis to settle down. It is well recognised that walking velocity can be altered in pathological gait patterns. Different approaches have been taken by different authors towards the walking velocity used at gait analysis. Some authors have instructed participants to walk at a constant speed as kinetic and kinematic parameters are known to be affected by walking speeds (Borden 1999, Fuchs 2002).

In this study participants were asked to walk at a self -selected walking velocity. This strategy has been widely used by other investigators previously (Simon 1983, Kaufmann 2001, Gok 2002, Mundermann 2005, Landry 2007, Astephen 2008, Zeni 2009).

The gait velocity improved significantly in all patients at the time of postoperative gait analysis. The preoperative gait velocity for the group of patients (with at least one arthritic knee) was 0.85 m/s, this was in the range of velocities reported in literature for patients with osteoarthritic knees (Gok 2002, Astephen 2008). The postoperative gait velocity (mean 1.15 m/s) was within the range reported for normal patients by some authors (Gok 2002, Astephen 2008). The 37.4% improvement in velocity was statistically significant (p= 0.01). The level of improvement is much better than the improvement seen in total knee replacements (Fuchs 2002, Saari 2005) and may be attributed to the preservation of the anterior cruciate ligament that is routinely sacrificed during total knee replacement, apart from the variations due differences in age and soft tissue adaptation to the effects of tricompartmental osteoarthritis.
The average stride length improved 10.79% in the postoperative group but not significantly (p=0.17), however cadence improved by 12.6% and this approached statistical significance (p=0.08). The comparison of gait velocities between different reports shows large variations even in strictly defined population groups. The average gait velocity in the preoperative group was lower than for postoperative group. Significantly lower gait velocities have been reported in patients with osteoarthritic knees ($p<0.05$) in literature (Stauffer 1977, Brinkman 1985, Messier 1992, Deluzio 2007, Astephen 2008). Similarly lower cadence and gait velocities have been reported in subjects with osteoarthritis of knees (Stauffer 1977, Brinkmann 1985, Deluzio 2007). These authors also reported longer double support period in osteoarthritic knees. According to these authors reducing gait speed and increasing double limb support time are pain-relieving strategies that work to reduce the compressive load on the knee joint. The higher double limb support time found in the preoperative measurements of the participants in this study can be explained by the lower gait velocity in this group. The significant improvement in the double limb support time in the patients assessed as part of this investigation may be attributed to increased gait velocity and cadence in the postoperative group. The effect of unicompartmental knee replacements was analysed by Catani et al, and they found that the temporo spatial parameters did not reach the levels found in the control (normal patients) group (Catani 2012), but the age of two groups was very different {70.3 (replacement) Vs 27.9 (control)}. This significant discrepancy in age will explain the difference in improvement levels following unicompartmental knee replacement

arthroplasty and normal patients in this group. The significant improvements in temporospatial parameters following replacement arthroplasty suggest that the compensatory pain relieving measures like increased double limb support time is not necessary anymore. It also implies that the compensatory mechanisms are not permanent and have the potential to revert back towards normal following successful surgical treatment. The individual parameters in these reports show large variations for values even in the normal population, let alone patients who have had surgical treatment between reports. These variations may be related to the length of walkway in the laboratory, the unaccustomed environment of the testing laboratory and the relative natural variation of these parameters in population groups reported (Sharma 2001).

8.4.1 Reliability and agreement characteristics of kinetic and kinematic parameters

As the kinetic and kinematic parameters were measured on two separate occasions, the reliability of measurement of individual kinetic and kinematic parameters was computed between the preoperative and postoperative measurement episodes. The Intra class correlation coefficients (ICC) classifications of Fleiss (less than 0.4- poor, between 0.4 and 0.75 - fair to good, and greater than 0.75 - excellent) were used to describe the range of ICC values (Fleiss 1979). The standard Error of Measurement is represented as a percentage of the parameter described and carries the unit of measure used with the parameter.

8.4.1.1 Reliability of Kinetic Parameters

The focus of the investigation was medial compartmental loading characteristics especially the adduction moment. An excellent agreement and reliability was found between measures for adduction moment (SEM= 0.2%, ICC = 0.99). The ICC is considered a relative measure of reliability that provides an indication of how well a measure is capable of differentiating among the patients in whom the measurements are taken. An ICC of 0.99 suggests that knee adduction moment is an excellent measure of medial compartment loading and is appropriate for use when assessing patients, such as those in this investigation. This finding is consistent with previous reliability reports that have evaluated healthy subjects. Kadaba (1989) tested 40 healthy subjects on separate days and reported that the knee adduction moment (abduction/adduction moment waveform expressed as a function of the gait cycle) was highly repeatable with a coefficient of multiple correlation of 0.9. Andrews (1996) tested 11 healthy subjects on separate days and also reported that the knee adduction moment was highly reliable with a mean difference in peak adduction moment between test days of 0.1%. Birmingham (2007) reported the reliability of measurement of adduction moments in a cohort of 31 patients with osteoarthritis of the knee. They found that an ICC of 0.86 was sufficiently reliable to differentiate population groups with knee osteoarthritis. Intra class Correlation Coefficient (ICC) of greater than 0.9 is considered to be sufficient to institute or alter treatment based on that investigation in clinical medicine (Birmingham 2007). This investigation was done predominantly to differentiate patterns of loading following unicompartmental knee replacements, not to use the information to decide the thresholds for treatment modalities.

In addition to evaluating reliability in patients with medial compartment osteoarthritis of the knee, Standard Error of Measurement (SEM) was calculated to define the variation in measurements that occur purely by chance. The SEM estimates the measurement error and facilitates the interpretation of an individual's peak knee adduction moment. For example, based on the SEM and the 95% confidence level, an individual patient's peak adduction moment obtained from gait analysis (mean of 3 trials on the limb of interest) could vary 0.2% simply due to measurement error alone based on the data from this investigation.

The adduction impulse measurement was found to be very reliable as well (ICC 0.99, SEM 2.1%). The reliability of measurement of adduction impulse as a loading measure has been reported previously. Apart from being a more representative measure of loading of the medial compartment when compared to PKAM, it was considered equally reliable in investigations in knees with osteoarthritis (Robbins 2008). In this investigation, the SEM showed that the variations in adduction moment impulse by 2.1% could be due to measurement error alone. Both coronal plane kinetic parameters namely PKAM and Add Imp measured in this investigation showed excellent reliability and agreement for repeated measures.

The sagittal plane kinetic parameters namely flexion and extension moments showed excellent reliability between measures (ICC=0.87). Traditionally sagittal plane kinetics and kinematics have been reported to have the highest reliability (Kadaba 1989, McGinley 2009), but this was not the case in this investigation. The sagittal plane kinetic parameters are known to be affected significantly by walking speeds (Lelas 2003). In this investigation, walking speeds in the preoperative and postoperative group of patients were significantly different, which might explain the greater variation in sagittal plane kinetic measures between the two measurement episodes (preoperative and postoperative) when compared to coronal plane kinetics. Inspite of the effect of walking speeds on sagittal plane kinetics it still showed excellent reliability between measures. The Standard Error of Measurement (SEM) indicated that flexion extension moment could vary by 21% due to measurement error alone.

The transverse plane kinetics measurement was least reliable amongst all the kinetic parameters, but it was still higher than 0.7 which is the value at which the reliability is considered excellent (Fleiss 1978). This has been reported by other investigators (Ramakrishnan 1991, Queen 2006). The SEM was 50% which implies that variations secondary to intervention (surgery in this investigation) should be greater than 50% to be considered significant.

8.4.1.2 Reliability of Kinematic parameters

The measurement of sagittal plane kinematic parameters was found to be very reliable in this investigation (ICC=0.98, SEM=7%), but this was better than the reliability measurement of sagittal kinetics. As discussed previously, the variation in sagittal plane kinetics may be attributed to the increase in gait velocities seen in postoperative patients. It has been reported that the sagittal kinematic measures are not affected as much by variations in gait velocities as sagittal kinetics are (Lelas 2003). This would explain the apparent discrepancy in the reliability measurement of kinetics and kinematics in the sagittal plane. In a review of literature, different researchers obtained good repeatability for sagittal kinematics both in adults and children (McGinley 2008). Although some other researchers have reported lack of reliability between measurements of sagittal plane kinematics (Schwartz 2004), this was not the case in this investigation.

The measurement of rotations showed excellent reliability and agreement (ICC=0.86, SEM=18%). This was contrary to reports by other authors. The large variability of measurements in knee joint rotation has been attributed to the positioning of epicondyle and malleoli markers, which are the basis for relevant anatomical frame orientations in that plane (Manca 2010).

The coronal plane kinematics was found to be the least reliable (ICC=0.66) kinematic parameter for measurement. The SEM measurement showed that up to 83% variability in measurement of varus -valgus angulation could be secondary to chance alone. This implies that the varus/valgus angles would have to double or halve to reach significance. The relatively low reliability of coronal plane kinematics has been reported by various authors. The significant influences of experimental error on coronal kinematics especially in children have been reported previously (Steinwender 2009, Schwartz 2004). According to these authors, these discrepancies can be caused by variations in the particular stages of the gait cycle and is related to the knee joint flexion/ extension. This implies that knee joint movements in the coronal plane are magnified when the joint is in flexion. The reliability of measurements of flexion extension angles and very similar measurements in the two groups achieved in this investigation may have improved the coronal plane kinematics.

As the skin markers are affected by movement of the skin, this gets amplified in subcutaneous joints like the knee. The knee joint is among the group of joints where skin movement is the most intensive. Therefore, variability may result from artifacts that occur following the movement of the markers on the skin (Leardini 2007).

8.4.2 Changes in kinetic parameters following unicompartmental replacement

The kinetic parameters measured in all three planes namely coronal, sagittal and transverse planes are discussed in this section.

8.4.2.1 Coronal Plane kinetics

The coronal plane kinetic parameters that were assessed as part of the investigation were the peak knee adduction moment (PKAM) and Adduction Impulse.

8.4.2.1.1 Knee Adduction Moment

Peak Knee Adduction Moment (PKAM) is a recognised proxy for medial compartment loading. It represents a single loading episode during stance phase, but disregards the cumulative loading for the duration of stance. Angular Adduction Impulse (Add Imp) is a more representative indicator of cumulative loading of the medial compartment. This investigation recorded both these parameters.

This study demonstrates that PKAM and Add Imp were higher in the osteoarthritic knees when compared to non arthritic asymptomatic knees in the same patients. The Increase in

PKAM in the osteoarthritic population has been reported by numerous previous authors on this subject (Sharma 2012, Thorp 2006, Astephen 2008, Zeni 2009, Kean 2012). Recent reports have shown an increase in Add Imp as well as PKAM in osteoarthritic knees. The non arthritic and asymptomatic knees were considered to be 'normal' for alignment and muscle forces for the population under consideration. This group was used for the purpose of comparison and has been referred to as 'normal' in this thesis. The PKAM in the non arthritic asymptomatic group was higher than the normalised values for the population (not age or sex matched). This might explain why the comparison of the increase in PKAM and Add Imp in the arthritic and non arthritic knees did not reach statistical significance. Although it has been an established concept that alignment influences PKAM and more recently Add Imp (Sharma 2001, Cerejo 2001, Brouwer 2007, Thorp 2006, Kean 2012), it appears that the muscular contractions across the knee joint and other soft tissue interactions do have a role as well. The present study does not explore this angle, but this effect would explain why inspite of presumably similar alignment in both knees to start off with, only the affected knee went on to develop arthritis earlier than the other one. The increased PKAM and Add Imp in the non arthritic knees may also suggest an increased preponderance to development of osteoarthritis of those knees later on in life. The increase in loading parameters in unaffected knees in patients with an osteoarthritic knee has been reported previously (Messier 1992).
The PKAM and Add Imp in the postoperative group decreased sufficiently to equal values recorded in 'normal' knees. This reduction was statistically significant. A significant increase in PKAM and Add Imp in osteoarthritic knees has been reported by numerous authors (Sharma 1998, Miyazaki 2002, Gok 2002, Deluzio 2007, Astephen 2008, Zeni 2009).From the results of this investigation it appears that the medial unicompartmental knee replacement arthroplasty restores these values to normal levels.

This reduction in PKAM has been reported by two authors previously (Deluzio 1999, Catani 2012). Deluzio (1999) reported gait analysis in thirteen patients and reported variation between the preoperative and postoperative measures. They were not able to demonstrate a uniform pattern between the preoperative and postoperative measures in these patients, with some knees showing significant improvements in kinematics while others showed significant variations in kinetics. Catani (2012) reported findings on 20 patients but did not report on the preoperative variables and the effect of surgery on coronal plane loading parameters. In the report by Catani, although unicompartmental knee replacements showed reduction in PKAM and significant improvement in temporospatial parameters, there is no analysis on direct comparison between preoperative and postoperative values for coronal plane kinetics. Moreover the normal group was not age and gender matched which makes direct comparisons difficult. In this thesis all patients were matched for age and gender simply by virtue of choosing the asymptomatic knees in the study group for this purpose. Moreover neither of these reports discusses the effect of alignment on the variations in coronal plane kinetics in the preoperative and postoperative groups.

The increased PKAM in osteoarthritic knees has been postulated to be secondary to varus alignment (Sharma 2001, Cerejo 2001, Brouwer 2007). As the perpendicular distance of the ground reaction vector increases from the centre of the knee the PKAM should increase. In varus knees the centre of the knee lies further away from the mechanical axis than in well aligned knees. This increase in the moment arm secondary to varus alignment has the potential to increase the magnitude of the knee adduction moment. A strong association has been reported between varus alignment and knee adduction moment in healthy patients and patients with osteoarthritis of the knees (Hsu 1999, Hurwitz 2002, Mundermann 2004) .Hsu reported a good correlation between alignment and PKAM in healthy subjects ($r = 0.824$, $p<0.05$). Previous authors (Sharma 2001) have reported significant correlation between varus alignment and risk of progression of arthritis. It has been inferred that the driving force in progression of arthritis in varus knees is the increase in PKAM secondary to altered alignment. Hurwitz reported a similar relationship between varus alignment (mechanical axis) and first peak knee adduction moment in subjects with medial compartment osteoarthritis of the knee (Hurwitz 2002). Varus alignment of more than 3° (joint malalignment) has been reported to increase the load passing through the medial compartment of the knee joint and risk of progression of osteoarthritis (Sharma 2001, Sharma 2008). Astephen reported no differences in the knee adduction moments between osteoarthritis groups of varying severity. This observation has been explained by authors by simply suggesting that PKAM is a function of alignment alone. The PKAM in similarly aligned knees would not be significantly different despite the difference in degrees of arthritis (Astephen 2008). These inferences have been drawn from population based studies, where the means between study groups have been compared.

In this investigation we found that the PKAM and Add Imp underwent significant reduction even in knees which did not undergo a correction in alignment. Previous reports have postulated that the sensory input from the articular surface like pain might affect loading parameters of the knee. The effect of intraarticular local anaesthetic injection on frontal plane kinetics has been studied previously (Henriksen 2006) .The authors reported an increase in peak adduction moments following the anaesthetic injection, but this did not reach statistical significance even though pain relief measured using a visual analogue score did. The findings in Henriksen's paper would suggest that the pain relief and sensory blockade would result in an increase in the PKAM and Add Imp, if modulation of sensory pathway was the mechanism by which the reduction in PKAM and Add Imp came about in osteoarthritic knees as the metal and polyethylene articulation would certainly have abolished sensory input from the articular surface.

This investigation did not explore the exact nature and effects of this potential sensory mechanism. This raises the obvious question of whether the improvement in PKAM and Add Imp is down purely to alteration in static alignment. This investigation attempted to answer that question by dividing the knees into three groups based on alignment using both the Hip Knee Ankle angle (HKA) and the location of mechanical axis. The PKAM ($p=0.01$) and Add Imp ($p=0.004$), reduced significantly in the absence of alteration in static alignment measured by the zone through which the mechanical axis passed, but this should be viewed in the light of angular measurements suffering from a Standard error of Measurement of 1 degree.

The effect of alteration of alignment became very significant in the corrected group (correction > 3 degrees). The ΔPKAM and ΔAdd Imp in this group showed a significant reduction even more than the reduction in the low correction (correction < 3 degrees) group of medial unicompartmental knee replacements ($p<0.05$). Thus it seems that when the correction exceeds 3 degrees of hip knee ankle angle (HKA) or when the mechanical axis moves greater than the width of one zone on the tibial plateau, the loading of the medial compartment reduces significantly.

Report II of study 1 reported in this thesis demonstrated a significant association of function (Bristol Knee Score) with alignment. That study did not have preoperative alignment data to compare the effect of function with correction of alignment, so it was impossible to detect if the relationship of good function to better alignment was secondary to corrections achieved at the time of surgery or due to the fact that the post operatively well aligned knees were well aligned preoperatively as well. Although a direct correlation between the findings of the two studies cannot be derived as they were on separate populations, it is clear that significant correction of alignment can result in significant improvement in loading characteristics in the coronal plane, which in turn may have a positive effect on function and survivorship in the long term. There are numerous reports of good function in medial unicompartmental knee replacements that have remained in significant varus malalignment (Gulati 2009). These reports give credence to the popular belief that placing the knee in its natural alignment without attempting to achieve correction at the time of unicompartmental knee replacement surgery is recommended. The reason attributed to the good function in these knees is the ligament balance and the possibility that the knee is unlikely to lose the soft tissue balance if releases have not been performed. The reason for good function in knees in study 1 which were well aligned might have been due to the fact that they were well aligned prior to surgery. There is very clear evidence from the present investigation that loading of the knee is significantly affected by alignment and that correction of static alignment by more than 3 degrees at the time of surgery improves the loading of the medial compartment significantly. Whether this improvement of loading in the medial compartment is of consequence either for function or survivorship has not been investigated in this thesis.

8.4.2.2 Sagittal Plane Moments

The opinion of investigators on variations of sagittal plane moments in early stance in osteoarthritic knees appears to be divided. In this investigation the extension moment in early stance increased significantly even beyond the value for normal knees.

Manetta (2002) reported no differences in the initial extension moment between patients with osteoarthritis of the knees and healthy control subjects ($p>0.05$). However, Astephen (2008) reported lower extension moments following foot contact in patients with severe osteoarhritis when compared with normal patients. Most authors agree that the decreased extension moment in osteoarthritic knees is a pain avoidance mechanism. Further evidence for this concept was reported by Henriksen who investigated the effect of administration of intraarticular local anaesthetic (Lignocaine) on kinetic parameters. They found a significant increase in the early phase extension moment following intraarticular sensory blockade with lignocaine (Henriksen 2006), suggesting the decrease in early phase extension moment in osteoarthritic knees is indeed a pain avoidance mechanism.

The early stance knee flexion moment in the arthritic knees was significantly lower than the normal group. This has been reported by previous authors that knee flexion moments in early stance were lower in people with osteoarthritis of the knee compared to healthy control subjects (Deluzio 2007, Landry 2007, Astephen 2008). Astephen (2008) reported that patients with severe osteoarthritis had a lower knee flexion moment in the early stance when compared to healthy control group ($p<0.05$). Authors of reports on investigations on joint moments have tended to attribute the variation of moments solely to alterations in alignment. Astephen reported that the patients with severe knee osteoarthritis also had a lower average peak flexion angle in early stance phase compared to the control group ($p<0.05$). The decrease in the knee flexion moment at this point in the gait cycle was attributed the lower knee flexion angle by the authors (Astephen 2008). Astephen (2008) reported that there were no differences in the flexion moment between the moderate and severe osteoarthritis groups even though the flexion angles were significantly different. This implies that the variation in knee flexion angle cannot be considered to be the sole factor responsible for the variation in flexion moments. This becomes even more obvious when the fact that the moderate and severe osteoarthritic groups in the report had similar levels of joint pain ($p> 0.0001$) is considered. As pain has been found to correlate with joint moment (Sharma 1998) this finding implies that similar pain levels may have resulted in the similar flexion moments or vice versa between the two severity groups even though the flexion angles in stance were different. This postulate is in keeping with our finding on coronal plane moments and static alignment, that moments are not solely the function of angular measurements alone.

In contrast, other authors (have reported higher flexion moments in early stance in subjects with osteoarthritis compared to healthy controls (Schipplein 1991, Al-Zahrani 2002). Schipplein observed that the group with osteoarthritis of the knees adapted their gait to a produce a higher external flexion moment which in turn increased the muscle force and joint compressive forces to improve knee joint stability. According to these authors, gait alteration could be used as a compensatory mechanism to increase the joint stability in osteoarthritis.

In the present investigation the flexion moment in early stance did not vary significantly between preoperative group and postoperative group even though the values were significantly lower than those for normal knees. The peak early stance flexion moment was significantly lower in osteoarthritic knees when compared to normal knees ($p<0.05$). This was in spite of the flexion angles being very similar in magnitude between the osteoarthritic and nonarthritic knees. The flexion moment increased following replacement arthroplasty but not significantly. The sagittal plane kinetics is a product of the interaction between the knee extensors, the knee flexors and knee flexion extension angle. The reduction in early stance flexion moment reported by previous investigators was confirmed by this investigation (Astephen 2008). Compensatory mechanisms to achieve pain relief have been postulated to be the reason for the decrease in joint moments by various authors. If pain relief was the only reason for change in early stance flexion moment following unicompartmental replacement arthroplasty, both flexion and extension moments in early stance would have been expected to increase following the surgery. There was a clear discrepancy between the effects on early stance extension moment which increased as expected while the early stance flexion moment did not change, contrary to the expected effect. This difference is even more interesting when flexion extension angles during stance are considered. There was no difference in the flexion-extension angles in stance between osteoarthritic knees and normal knees and between preoperative and postoperative groups. This has led us believe that joint moments are not simply direct functions of joint angle even when normalised for weight and height and when anthropometric measurements remain relatively unchanged as it has been in the patients analysed in this thesis.

The mechanisms adopted by the body to compensate for the effects of osteoarthritis are well documented in literature. Compensatory trunk lean and increased toe out have been reported in osteoarthritis literature to be the reasons for decreased coronal plane joint moments in osteoarthritic knees. These compensatory mechanisms are achieved by alterations in muscular forces and soft tissue interactions across joints. Some of these alterations in soft tissues must become irreversible in the period during which the osteoarthritis progresses to the 'severe' bone on bone articulation. These compensatory mechanisms that have become permanent should be considered to be the reason for the discrepancy in joint moments despite similar joint angles.

The late stance knee extension moment increased following the replacement arthroplasty. This was not statistically significant. The late stance extension moment in arthritic knees was lower than normal knees. This has been reported by previous authors (Messier 1992, Astephen 2008). These authors have suggested that subjects with knee osteoarthritis reduce the knee extension moment in late stance in order to reduce knee compressive forces by decreasing their walking speed. This is a compensatory pain relieving phenomenon. The improvement in gait speed in the post replacement arthroplasty patients may account for the small but insignificant increase in extension moment at this point in stance phase.

The kinetic pattern following total knee replacements have been reported. Patients following total knee replacement have been reported to show an increase in early stance extension moment in keeping with the patterns exhibited by healthy subjects. The early stance flexion moment in many total knee replacements are shown to have been replaced by extension moment. This is typically seen in 28-50% of patients reviewed (Chassin 1996, Smith 2004). The clear discrepancy reported in loading patterns between total knee replacements in literature and the unicompartmental knee replacements in this investigation can be attributed to the differences in inherent stability which may result in the early firing of the compensatory muscle groups leading to different moments. The anterior cruciate ligament being sacrificed in total knee replacements may have a significant effect on this phenomenon. It would be interesting to know how these parameters are affected when compared between the nonstabilised and stabilized versions of knee replacements, as that would be the only way to clarify the role of stability in different gait patterns. The literature is lacking in this aspect.

8.4.2.3 Transverse Plane Kinetics

Transverse plane kinetics in this investigation did not show significant differences between the arthritic knees and the non arthritic knees. In the gait analysis literature, transverse plane moments have not been studied as extensively as sagittal and coronal plane moments but the importance of transverse plane moments in initiation and progression of osteoarthritis have been reported previously. It has been suggested that changes in transverse plane mechanics at the knee can initiate degenerative changes by placing new loads on regions of the articular cartilage that were unaccustomed to those load levels previously (Andriacchi 2006). While transverse plane mechanics have been implicated in the progression of knee osteoarthritis (Andriacchi 2006), only a few studies have quantified differences in transverse plane kinetics at the knee (Gok 2002, Landry 2007). Investigators (Kaufman 2001, Landry 2007) have reported no significant differences in transverse plane kinetics between knees with osteoarthritis and knees in normal population. Our results did not show significant differences in the transverse plane moments between the non arthritic knees and arthritic knees. The postoperative values for transverse plane kinetics following unicompartmental knee replacements were not significantly different from the preoperative values either.

Catani (2012) reported that in patients who have undergone unicompartmental knee replacements, the external rotation moments did not show significant differences, but the internal rotation moment was significantly lower following replacement arthroplasty. These variations in values reported for transverse plane kinetics in the literature may be due to the effect of marker placement around the knee with the resultant variation in axes between investigations and also the fact that the rotation moments are very small in magnitude when compared to sagittal plane and coronal plane kinetics. The transverse plane kinetics was demonstrated to have lower reliability and agreement when compared to sagittal and coronal plane kinetics in gait analysis.

8.4.3 Changes in kinematic parameters following unicompartmental knee replacements

The changes in the kinematic patterns following unicompartmental knee replacements in all three planes are discussed in his section.

8.4.3.1 Sagittal plane kinematics

The flexion extension range in stance did not vary significantly between the arthritic and normal groups. Furthermore the replacement arthroplasty did not appear to have a significant effect on flexion range. The extension at initial contact has been reported to be reduced in osteoarthritic knees (Mundermann 2005). There are several reports in literature where a decrease in the flexion range was found in arthritic knees (Mundermann 2005, Astephen 2008, Zeni 2009). This reduction in the flexion range is reported to worsen with progression of arthritis. This is believed to be a pain avoidance strategy and similar to quadriceps avoidance gait. In this investigation there was no difference in the flexion range between arthritic and nonarthritic knees. All patients were those with unicompartmental osteoarthritis. This may have been the reason why there were no significant differences. Differences may be elicited if patients with tricompartmental knee osteoarthritis are analysed. In this investigation the flexion-extension range through stance was found to be similar between three groups, which occurred in spite of the improvement in gait velocity following replacement. Gait velocity has been discussed previously as a significant factor in the alteration of sagittal plane kinetics and kinematics. It has also been reported that the varus aligned knees ambulate with more knee flexion during early and midstance. Greater knee flexion in stance could predispose these varus-aligned knees to problems, as greater knee flexion in stance is associated with greater tibiofemoral loads (Nagura 2006). In this investigation the knee flexion angles did not appear to change with osteoarthritis or following replacement.

8.4.3.2 Coronal plane kinematics

An increase in the mean adduction angles was demonstrated in patients with unicompartmental osteoarthritis. This improved following replacement arthroplasty. The adduction excursion was also increased in osteoarthritic patients. This did not improve following unicompartmental knee replacement. The increase in the adduction angle in osteoarthritic knees has been reported previously (Briem 2009, Nagano 2012).It is believed that the increase in the adduction angles in osteoarthritic knees represent the very early phase of varus thrust, which is a visual phenomenon observed in latter stages of osteoarthritis (Chang 2004). The replacement arthroplasty improved the adducted (varus) alignment at early stance (foot contact) of these knees. The adducted (varus) alignment seemed to improve even more in those knees where a correction of static alignment was achieved at the time of surgery. None of the variations were statistically significant. The mean adduction angle was different between the preoperative and postoperative groups. But authors of gait analysis literature have suggested using varus excursion as a parameter as the starting point measurements of angles may be offset, due to errors that creep in due to marker placement and skin mobility. The adduction (varus) excursion did not differ significantly between the preoperative and postoperative groups in his investigation. The persistence of increased varus excursion, inspite of surgical treatment where a correction of static alignment was achieved is indicative of the fact that some of the compensatory mechanisms around the knee that is achieved through alteration in soft tissue tension does become permanent with time, and may not revert back to normal in spite of replacement of the arthritic joint surface. Even more interesting is the finding that the adduction moments decreased in spite of the varus excursion not being altered. This gives credence to the view previously expressed in this thesis that moments are not solely the function of angular measurements and that tension in the soft tissues (muscles and ligaments) make a significant contribution as well. It is even more important to bear in mind that large variations in coronal plane kinematics in gait analysis literature may be due to the low reliability of coronal plane kinematic measurement. In this investigation 83% of the variation in coronal plane kinematics could be due to chance alone.

8.4.3.3 Transverse Plane kinematics

The internal rotation was significantly reduced in the arthritic knees. This has been reported previously by Nagano (2012). The reduction in internal rotation is said to be a compensatory pain relieving gait modification mechanism that occurs in toe out gait. Toe out gait as a compensatory pain relieving mechanism has been investigated and reported extensively in gait analysis literature. In normal gait, the foot progression angle is around five degrees, indicating toes pointing slightly outward (Guo 2007). Toe-out gait is an increase in foot progression angle resulting in the foot being held in an externally rotated position (Jenkyn 2008) due to alteration of rotation at the knee. It has been reported that toe out reduces the second peak of the KAM but not the first peak (Guo 2007, Lynn 2008). This may explain the loss of the typical double hump curve that is seen on measurement of adduction moments in arthritic knees. It is interesting to note that the pattern of the adduction moment normalises following unicompartmental knee replacement. Toe-in gait, defined as a decrease in foot progression angle from baseline through internal foot rotation, has been studied to a much lesser degree when compared to toe out gait. Although toe in gait has been reported to result in reduced first peak KAM in healthy adults (Lynn 2008), it has not been reported as a pain and load relieving compensatory mechanism commonly seen in osteoarthritic patients, in literature. This may be due to the intuitive difficulty in achieving an internally rotated or toe-in gait as a compensatory mechanism to improve loading in osteoarthritic knees. One of the consequences of this decreased internal rotation is the loss of screw home mechanism very early in the progression of osteoarthritis in the knee. Even though the internal rotation excursion was reduced in arthritic knees compared to normal knees, the external rotation excursion did not vary significantly between the arthritic and nonarthritic groups. The reduced internal rotation did not improve significantly inspite of replacement arthroplasty. The external rotation did not vary significantly between groups and following surgery.

8.4.4 The effect of sagittal plane kinematics on sagittal plane kinetics

This investigation did not show significant variation in sagittal plane kinematics between the preoperative and postoperative groups. The only significant difference in the sagittal plane kinematic parameters occurred in early stance extension moment, but this could not be correlated to alteration in extension or flexion angles measured clinically or as part of the instrumented gait analysis.

8.4.5 The effect of transverse plane kinematics on transverse plane kinetics

This investigation did not demonstrate a significant variation in transverse plane moments between the preoperative and postoperative groups. Although there was an improvement in internal rotation parameter of knee kinematics, it did not seem to affect the kinetics significantly.

8.5 The effect of static and kinematic coronal plane alignment on coronal plane kinetics

It has been reported that a greater adduction (varus) angle at the knee will shift the overall knee load further onto the medial tibiofemoral compartment and can have a significant influence on the progression of medial compartment osteoarthritis (Andriacchi, 1994). This effect of static alignment on medial compartment loading of the knee is well recognised and accepted. The loading of the knee is dynamic and the angular relationships at the knee can vary significantly during gait. On analysing the patterns of dynamic loading of the knee, it becomes only intuitive that the kinematic parameter of peak adduction angle would correlate highly with peak knee adduction moment. Various investigators have attempted to find the relationship of kinematic variables and their influence on the coronal plane kinetics. The parameters that have been commonly investigated are peak adduction angle, mean adduction angle and adduction excursion. During the stance phase, peak adduction angle and peak adduction moment are reported to happen at similar points (Barrios 2010) which is used as a justification for the view that the peak adduction moment is a function of the peak adduction angle. This did not appear to be the case in this investigation, where the peak adduction angle occurred much later during stance. If the peak adduction moment and adduction impulse were functions of the peak adduction angle, it would follow that peak adduction angle should have a significant influence on these coronal plane moments. In our study the reduction in both peak adduction moment and adduction moment impulse occurred in spite of very similar peak adduction angles in the preoperative and postoperative groups. The adduction angle at the beginning of stance was significantly higher in osteoarthritic knees compared to the normal knees, but not in the group following replacement arthroplasty. Increased adduction (varus) in osteoarthritic knees is secondary to loss of articular cartilage and bone remodelling as a result of increased loading of medial compartment seen in these patients. This variation in alignment secondary to loss of articular cartilage gets corrected at the time of surgery. The lack of symmetry in the improvement of kinematic and kinetic parameters can be explained by factors like variations in co-contraction of the muscles that cross the knee and functional coronal plane laxity that is seen in osteoarthritic knees and normal knees (Schmitt 2007).

Previous investigations on radiographic alignment did not lead to uniform findings on the effect of variables that affect dynamic knee loading. The positive correlation between static alignment (varus alignment) and medial compartment loading has been agreed upon by some, but not all previous authors on this subject (Miyazaki 2002). The reason for variation in the relationship of static frontal plane alignment to peak adduction moment can be manifold. The most influential of these is the two-dimensional nature of radiography, as measurement of angles on radiographs is prone to errors (Cooke 2007). These errors may be related to errors of measurements by the same investigator, or the variations in the apparent alignment of the limbs at the time of the radiograph being taken. To reduce the variations secondary to measurement on radiographs, investigators have attempted to standardise the radiographic measurement and the biomechanical measurement by ensuring identical position for the static calibration and for the alignment radiograph by ensuring identical position of the feet at the time of obtaining radiographs by using foot maps (Barrios 2012). In this investigation the radiological assessment was done at a different site of the gait measurement and was obtained as per a standardised protocol. We calculated reliability and agreement between the same radiographs being assessed at different points of time and also calculated the standard error of measurement for alignment views of the same limb taken at different points of time. It was established that the standard error of measurement was approximately one degree, while the standard deviation was 2.5 degrees. In order to be absolutely certain that the variations in angular measurements was not erroneously estimated, we used 3 degrees as the threshold that determined significant alteration of alignment. The unicompartmental knee replacements where a correction of alignment was greater than 3 degrees, the reduction of coronal plane kinetic parameters (ΔPKAM and Δ Add Imp) was significantly related to the correction, but not the final Hip Knee Ankle angle.

Radiographic measures of knee alignment are also sensitive to positional error in the sagittal plane. If standing in slight knee flexion, lower extremity external rotation may appear as varus angulation, while internal rotation may appear as valgus angulation (Moreland 1987). In our study this was not a significant problem at the analysis as we found that the flexion angles measured clinically and electronically at gait analysis did not change between the two measurements. In most study designs, the radiographs are taken in bilateral stance and the alignment of one limb is then related to single-limb weight-bearing during gait analysis. It has been reported that radiographic alignment angles increase in the varus (adduction) direction when moving from supine to double-limb standing posture to single-limb stance (Specogna 2007). Therefore there is a case to use alignment radiographs done in single leg stance. Radiographs done in single limb stance have been found to have improved the relationship between radiographic alignment and the knee adduction moment (Barrios 2012) as the alignment measure is a much more precise measurement of the varus angle that might be relevant to single leg stance during gait analysis. The variation in the findings between different investigators on the effect of static alignment on coronal plane kinetics may be explained by the inaccuracies in the measurements mentioned above. In the present investigation, the same methodology was followed for alignment measurements before and after the operation. Apart from the fact that alignment radiographs only provide information about alignment in the static position, the knee joint loading can be heavily influenced by alterations in dynamic alignment.

A study analysed the combined effect of peak adduction angle and radiographic alignment to account for variation in the knee adduction moment data. Although the addition of radiographic alignment to peak adduction angle would have been expected to significantly increase the correlation between adduction moment and alignment, this was not found. It has been suggested by the authors that radiographic alignment does not provide unique information beyond that of peak adduction angle when examining the alignment-moment relationship (Barrios 2012). Although this suggestion is well placed in gait analysis research, in a surgical model like unicompartmental knee replacements, the radiographic alignment view has a very relevant place especially when one considers the fact that the only correction that can be achieved at surgery is static correction at different points of range of motion. In this investigation we found that varus- valgus measurement (kinematic analysis) had a significantly lower reliability and agreement (SEM= 83%) when compared with radiographic alignment measure, which made it a far more useful variable.

As a measure of cumulative loading throughout stance adduction impulse (Add Imp) rather than peak knee adduction moment (PKAM) which is a loading measure at an instant, was found to be reliable within 2% error secondary to chance. The use of Add Imp has been reported previously by authors to be a more representative measure (Thorp 2006, Robbins 2008, Barrios 2010). In the present investigation adduction impulse behaved similarly to Peak adduction moment, although the differences in adduction impulse between preoperative and postoperative groups were larger and considerably more significant. This is understandable as the magnitude of the impulse was always significantly greater than that of PKAM as the Add Imp was the time moment integral of the adduction moment plot.

Apart from the above mentioned potential flaws in measurement of alignment parameters, the skin markers and modelling of local coordinate systems on which gait analysis is based can lead to variations in measurements. The different algorithms related to the marker sets, used to determine the hip joint centres during gait analyses, would directly affect thigh kinematics which in turn will affect the angular measurements at the knee. In this investigation, this was not an issue as the same marker protocol was used and only the differences between preoperative and postoperative groups for a standardised protocol was analysed.

8.6 Are alignment parameters predictors of loading?

From a cause effect point of view the role of alignment has been found to have a definite role in the progression of osteoarthritis. Although it is intuitive to consider that alignment which increases the risk of progression should increase the risk of initiation of osteoarthritis, but research evidence has not backed this up. The consensus appears to be that alignment has a significant effect on progression of arthritis but may not have a similarly significant effect on its incidence (Hunter 2009). Peak Knee adduction moment (PKAM) is considered to be the most influential factor in producing medial joint force in knee joints with varus deformity (prodromos 1985, Wang 1990). Previous studies have shown that the adduction moment negatively correlates with joint space width (Sharma 1998) and positively with varus alignment (Wada 2001) in knee osteoarthritis. The loss of joint space accentuates the varus alignment in medial compartment osteoarthritis of the knee. Most of the evidence has been gleaned from longitudinal studies which have analysed incidence and progression of osteoarthritis and factors that affected them. The progression of arthritis in the presence of favourable mechanical environment has been well established, but the effect of alteration of alignment on the loading and subsequently the effect on progression of osteoarthritis has mostly been implied. The literature on the effect of foot wear modification and valgus unloader braces has shown a definite decrease in the adduction moments which in turn is proposed to decrease the progression of osteoarthritis. All these interventions are believed to improve loading by improving the coronal plane alignment. The parameters that reflect the coronal plane alignment are Hip Knee Ankle (HKA) angle and kinematic parameters like mean adduction angle (MAA), peak adduction angle (PAA), and adduction excursion. On regression analysis it was found that the mean adduction angle was a better predictor of both the adduction impulse and peak knee adduction moment (PKAM) in our investigation. The HKA was a significant predictor of adduction impulse and PKAM in the postoperative knees while the MAA was not. The greater predictive value of the mean adduction angle (MAA) when compared to HKA has been reported previously in patients who underwent upper tibial osteotomy. The positive relationship between MAA and PKAM was seen only in preoperative patients but not in postoperative patients (Leitch 2013). These findings only prove that static and dynamic alignment parameters are interrelated as they measure essentially the same parameter but using different methods. Although they are significant variables that affect loading, they are not always good and reliable predictors of alteration in loading. This prompted us to use the change in PKAM (ΔPKAM) and change in adduction impulse (ΔAdd Imp) as the parameters analysed against alteration of alignment measures (Δ HKA and ΔMAA). These variables were not found to be reliable predictors either. On review of the magnitude of values, it was found that for very similar alterations of MAA and HKA the ΔAdd Imp was found to be very variable. This was because the magnitude of adduction moment (peak and impulse) was variable even between knees that had similar or identical HKA or MAA. We used the percentage variation of PKAM and Add Imp in our study. The %Δ PKAM being the Δ PKAM expressed as a percentage of pre op PKAM. The %Δ Add Imp being Δ Add Imp expressed as percentage of preoperative Add Imp.

8.7 Correction of alignment predicts reduction in loading

The effect of realignment osteotomies around the knee have been studied and reported by other authors. In a recent investigation Leitch et al reported approximately fifty percent variation in adduction impulse following varus or valgus producing osteotomies (Leitch 2013). They found in their study which included controls that the loading parameters did not differ significantly between the controls and the postoperative knees having achieved similar alignment as controls. In our investigation a significant reduction of both adduction moment impulse and peak adduction moment was seen in the postoperative group. When improvement in peak knee adduction moment (%Δ PKAM) and improvement in adduction impulse (%Δ Add Imp) were analysed for relationship with Δ HKA and ΔMAA, both were found to be significant predictors for improvement in PKAM and Add Imp. The Δ HKA was found to be a bigger predictor of improvement in both PKAM (%Δ PKAM) and Add Imp (%Δ Add Imp) on multiple regression analysis. The Δ HKA was found to reliably predict (R^2 = 0.9) variation in adduction impulse. The coefficient of regression suggests that 91% of the improvement in Add Imp could be attributable to variation in HKA. The Δ HKA was a less reliable predictor of variation in PKAM (R^2 = 0.46). For every one degree correction of HKA angle, the adduction impulse improved by 7%. For every three degree increase in the HKA, which was the median correction value, there was a 21% decrease in the adduction moment. We found that alteration in HKA angle in the present series would have resulted in improvement of adduction impulse from 7% to 43% corresponding to 1 degree to 6 degree improvement in HKA angle.

Chapter 9

Does articular surface regulate its own loading?

This chapter outlines the phenomenon of mechano transduction in human tissues and attempts to compare the results of coronal and transverse plane moments in three groups of knees of comparable alignment and muscular forces inorder to answer the question whether articular surfaces regulate its own loading. The nonarthritic asymptomatic knees (n=10), arthritic knees (n=18) and replaced knees (n=18) were used for the analysis

9.0 Evidence for cartilage response to mechanical loading

Mechano transduction (tissue response to mechanical loading) is an established phenomenon that has been reported extensively in orthopaedics literature. Wolff's law originally proposed by Julius Wolff in 1892 describes how new bone is laid out along the lines of stress and explains how lack of loading can result in decrease in bone mass. A similar effect of mechanical loads on articular cartilage has been described as well. Animal studies have demonstrated that prolonged joint immobilisation lead to cartilage thinning, tissue softening, and reduced proteoglycan content resulting in matrix fibrillation, ulceration, and erosion (Jurvelin 1986). Lack of activity has been reported to lead to osteoarthritis like changes in hamster model, as characterised by reduced proteoglycan content, fibrillation, pitting, and fissuring (Otterness 1998). It has been shown that in the absence of joint loading, patients with spinal cord injuries showed progressive thinning of knee cartilage in the absence of normal joint loading at a rate which was higher than that observed in osteoarthritis (Vanwanseele 2002). However, the effect on articular cartilage following short term immobilisation in a canine model was largely reversible and remobilisation of the joint led to restoration of matrix (Haapala J 1999). There is sound evidence that individuals engaging in regular activity are less prone to incidence of osteoarthritis, since frequent dynamic loading in the physiological range will increase cartilage thickness and maintain normal cartilage integrity (Fransen 2002).

On the other hand, literature on osteoarthritis is replete with reports of how mechanical loading is responsible for the development and progression of osteoarthritis. This has been addressed earlier in the thesis. It is a valid question whether the articular surface has any effect on how this loading is regulated.

9.1 Gait parameters used for assessment of loading

The unicompartmental knee replacement is the ideal model for assessment of the contribution of articular surfaces to the regulation of loading. In a medial unicompartmental knee replacement model only the articular surfaces of the medial compartment is replaced, the rest of the knee is maintained in its prior natural state as much as possible in a surgical model.
The kinetic parameters measured are those in the three planes namely coronal plane, transverse plane and the sagittal plane. Of the three the sagittal plane kinetics are the ones most likely affected by alteration in the power of the flexors like hamstrings and extensors like quadriceps. The coronal plane kinetics and transverse plane kinetics are least likely to be affected by muscular imbalances and are mostly a function of the ligaments. Moreover the coronal plane kinetics like the Peak knee adduction moment (PKAM) and angular adduction impulse (Add Imp) have been extensively studied and validated as loading measures. For these reasons the coronal plane and transverse plane kinetics were chosen for this analysis. In the reliability analysis both coronal and transverse plane kinetics were found to have excellent reliability between measures.

The one factor that would have affected the coronal plane kinetics was alignment and this was measured using long leg alignment views and the kinematic variables measured during gait analysis.

The second potential problem that was encountered was that the alignment of the individual knees prior to being affected by arthritis was not known. This problem was resolved by using the unaffected asymptomatic knees in the same patient group for analysis. The knees being symmetrical for alignment and muscular force is very likely.

9.2 Results

The nonarthritic asymptomatic knees (n=10), arthritic knees (n=18) and replaced knees (n=18) were used for the analysis.

Coronal plane kinetics; The adduction moment curve for the postoperative knees was nearly identical to the knees that were unaffected and asymptomatic (Figure 9.1). The 1st and 2nd peak adduction moments as well as the angular adduction impulse were nearly identical.

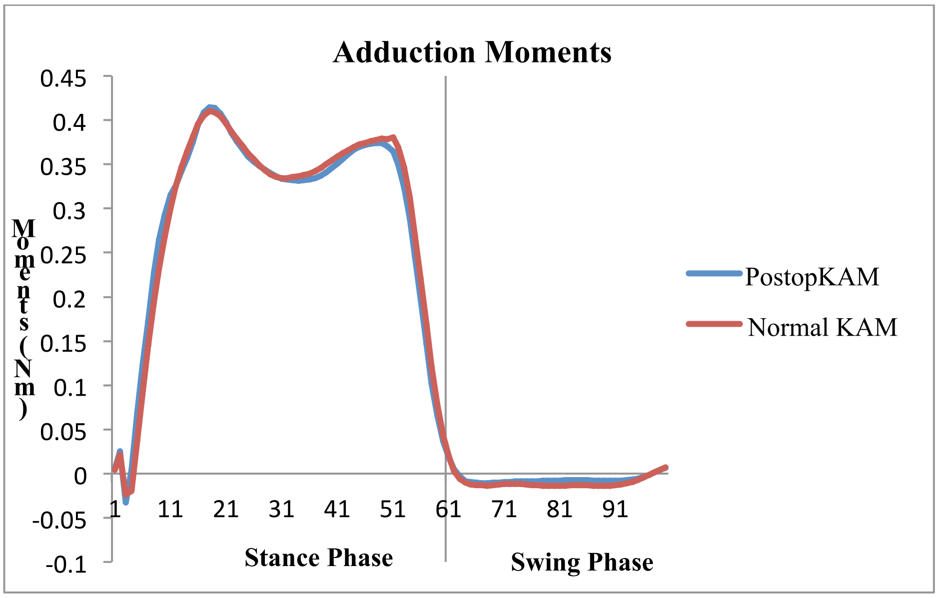


Figure 9.1Coronal plane kinetics in the postoperative group and normal knees.

The transverse plane kinetics between the non operated group and replaced group was nearly identical as well.

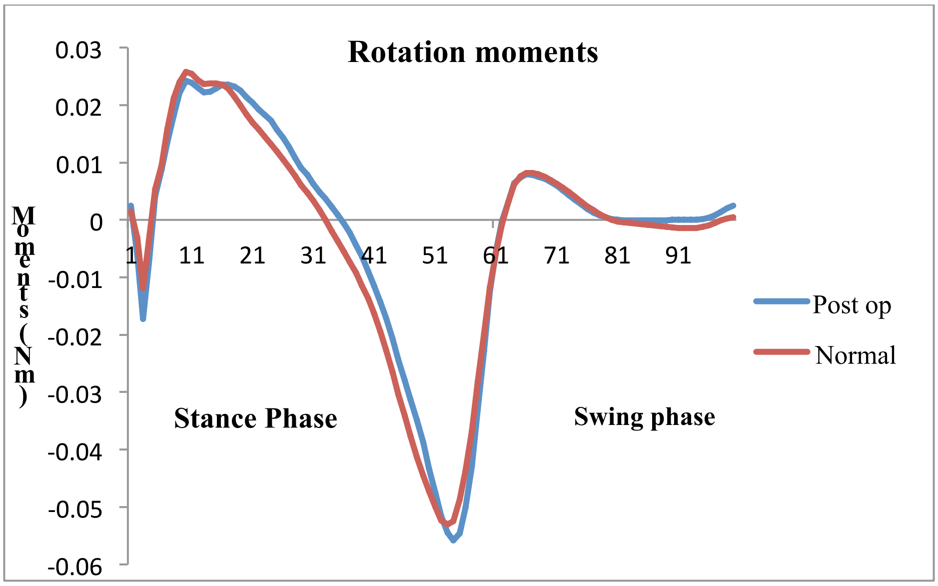


Figure 9.2Transverse plane kinetics in the postoperative group and normal knees.

Table 9.1 Coronal plane and transverse plane kinetic parameters.

	AddImp	1st PKAM	2nd PKAM	ER Moment	IR Moment
Normal	17.77	0.41	0.379	0.025	0.053
Post op	17.67	0.414	0.373	0.024	0.055

9.3 Discussion

This analysis makes two vital but rational assumptions. Firstly, that the knees were symmetrical for alignment prior to the development of medial compartment osteoarthritis. Secondly, that the loading of the medial compartment resulting purely from the muscular interaction across the knees are equal for both knees during the stance phase of gait. The loading resulting from the distribution of body weight between the knees during stance is comparable and is measured during gait analysis.

The coronal plane kinetics measured namely the adduction moment curve, the peak adduction moment and adduction impulse did no shoe significant variation between the normal knees and the replaced knees implying that if the alignment of the arthritic knees (surgical model) were symmetrical to the contralateral side prior to the development of medial compartment osteoarthritis and if this was restored with replacement arthroplasty, then the effect of articular cartilage in regulation of its own loading as measured by the coronal plane kinetic parameters appear identical to the effect of metal and polyethylene articulation. The analysis of transverse plane kinetics, which showed very little difference in the rotation moments between the replaced group and the normal knees support this conclusion.

The effect of loading on articular cartilage is well documented in canine models (Jurvelin 1986, Otterness 1998) and in human joints using MRI scans (Vanvanseele 2002). The effect of loading on cartilage has been studied by various authors is different contexts. Beaupre (2000) used mechanical modelling analysing the effect of compressive stress and octahedral shear stress on the formation of diarthrodial joints. The mechanical models predicted that physiological octahedral shear stress resulted in growth. The findings on these finite element models were proven in experimental designs. Mechanical loading of explanted femoral condyles in- vitro showed morphological changes indicative of secondary ossification centre formation in the growth plate cartilage (Sundaramurthy 2005). Although in experimental conditions it is difficult to isolate the shear and compressive loads due to the shape of the condyles, this evidence is valuable proof for the predictions on the experimental models.

Genetic and molecular influences on articular cartilage formation are influenced by the mechanical modulations. Decorin found in several connective tissues such as tendon, annulus fibrosus and neonatal growth plate interacts with type II collagen fibrils and regulates chondrocyte proliferation. It is postulated that decorin is sensitive to mechanical stresses and regulate both type I and type II collagen fibrils and thus endochondral ossification (Mochida 2003). Chondrocytes in the deep and middle radial zones, which are primarily loaded under hydrostatic pressure and experience little strain and fluid flow, synthesize and maintain high amounts of glycosaminoglycans, uronic acid, and type II collagen (Franzen 1981). In contrast the flattened superficial cells that are subjected to fluid flow and matrix consolidation in addition to hydrostatic pressure, synthesize and maintain proportionally higher amounts of collagen relative to proteoglycans, and type I collagen may be synthesized in addition to type II collagen (Muir 1970). The variations in histomorphology lead to variations in mechanical properties. The tensile modulus of the superficial zone is twice as much as the deep zone while the matrix compressive load is one third of that of the deep zone (Krishnan 2003). The effects of different types of loads on the chondrocytes and extra cellular matrix have been studied. Within the normal physiological loads the articular cartilage chondrocytes expressed increased levels of matrix proteins in response to hydrostatic pressures, while shear stresses induced formation of nitric oxide which is known to increase cartilage apoptosis (Lee 2002). Even though the formation of the ossific nucleus is vital in separating the articular cartilage from the physis, the mechanical environment that the entire cartilage is subjected to is responsible for the differentiation of growth cartilage and articular cartilage. This differentiation is regulated by transcription factors in articular cartilage and growth cartilage that are found to be the same, but have opposing effects on chondrogenesis and osteogenesis (Sandell 2002).

Although there is a large amount of evidence detailing the effect of loading on articular cartilage, there have been no investigations exploring how the articular cartilage affects its own loading in human knees. This investigation has allowed comparison of parameters between two comparable groups where the only difference is replacement of articular cartilage with the unicompartmental prosthesis.

9.4 Conclusion

The evidence from this analysis indicates that the articular surfaces have no effect on the regulation of its own loading.

Chapter 10

Conclusions

10.1 Conclusions

This investigation was set up to explore if the articular surfaces had any influence on the loading of the knee. The model chosen to evaluate this was the medial unicompartmental knee replacement whose unique characteristics have been discussed previously. The investigation allowed us to analyse the effect of replacement arthroplasty on the loading patterns of the knee and the effect of coronal plane alignment on the coronal plane loading. The data collected was analysed for the effect of medial unicompartmental knee replacement arthroplasty on the kinematics of the knee as well. This was done in study 2

In order to achieve the above objectives study 1 was set up to establish the improvement of the symptoms reported in literature in the surgical model. The main aim of study 1 was to assess if the improvement in symptoms as described in the literature following unicompartmental knee replacements is consistent enough to use the model for the purpose of assessment of loading of the knee in Study 2.

The data collected in study 1 was used to analyse the effect of coronal plane alignment on function as measured by the 50 point Bristol knee score.

1) Study 1 revealed that unicompartmental knee replacements showed a 10 year survivorship of 94% and a 15 year survivorship of 87% for medial unicompartmental knee replacements which is comparable to published reports from numerous other authors.
2) The analysis of data for the effect of alignment on function as published in Report II of study1 revealed a significant positive correlation ($p<0.01$) between alignment and BK score. This was contrary to some previous reports which did not find a linear relationship. This investigation revealed a quadratic relationship.
3) The coronal plane kinetic parameters (PKAM &Add Imp) were found to be most reliable between measures (ICC=0.99) amongst all kinetic parameters. Both PKAM and Add Imp improved significantly following medial unicompartmental knee replacements.
4) There was a significant difference in the improvement of PKAM (5%) and Add Imp (20%) when there was a significant correction of alignment. This has not been reported previously.
5) The alignment as measured by Hip Knee Ankle (HKA) angle and Mean Adduction Angle (MAA) were significant predictors of improvement in loading (%ΔAdd Imp).

Of these parameters the HKA angle was the more significant predictor (r^2 = 0.90). For every degree of correction achieved, loading of the medial compartment improved by 7%. This has not been reported previously.

6) This investigation as revealed that the articular surfaces do not have any effect on the regulation of its own loading. In fact the loading parameters in the post operative knees were found to be identical to those of the unaffected knees (normal). This has not been reported previously.
7) The kinetic parameters on the transverse plane did not vary significantly between the preoperative and postoperative groups.
8) The only sagittal plane kinetic parameter that showed significant improvement was the early stance extension moment. The other parameters did not show significant change.
9) The sagittal plane kinematics was remarkably similar between the preoperative, postoperative and normal knees.
10) The time - distance parameters showed significant improvement following unicompartmental knee replacement.
11) The investigation revealed a significant improvement in WOMAC and modified knee society scores following unicompartmental knee replacement.

10.3 Clinical Implications of Research

The role of alignment in joint replacement of the knee cannot be overemphasised. A great amount of time and resources have been spent to achieve perfect mechanical aligment in the coronal plane of the knee. Large amount of financial resources have been spent on facilities like computer navigation in order to achieve precise alignment at the time of surgery. This investigation has reiterated the importance of alignment. Study 1 establishes that in a well aligned unicompartmental knee replacement, the likelihood of achieving better function was much higher than in a malaligned knee. Although achieving alignment has been to improve survivorship more than function, improvement in scores seen in this investigation maybe due to the knees being well aligned even prior to the replacement surgery. The influence of alignment on survivorship following medial unicompartmental knee replacement has been traditionally accepted by numerous authors. The report that malalignment significantly affects survivorship in fixed bearing unicompartmental knee replacements is both informative and thought provoking (Emerson 2002). It becomes even more relevant when keeping some residual malalignment is part of the surgical goal (Kinematic alignment) when unicompartmental knee replacement is achieved using a mobile bearing prosthesis. This raises the obvious question whether improvement in coronal plane alignment actually translates into improvement in dynamic loading through the gait cycle and other actvities. Study 2 has demonstrated that atleast through the gait cycle, correction of coronal plane alignment results in significant improvement of medial compartment loading. This improvement in alignment and subsequently loading should have a favourable impact on the loading, bone strains and probably wear characteristics of unicompartmental knee replacements. Although the effect this improvement in loading may have on longterm survivorship is yet to be fully established, it is the opinion of the authors that all things being equal a better aligned unicompartmental knee replacement would have a better loading environment that may lead to longer survivorship. The improvement in loading would positively impact the bone strains on the medial tibial plateau, which has been postulated to be a possible cause for medial sided pain following medial unicompartmental knee replacement. The investigation did not clarify why mobile bearing unicompartmental knee replacements inspite of being kinematically aligned has been reported to have excellent survivorship. This may have to do with the strict criteria of exclusion of knees with varus greater than 15^{o} or fixed varus deformity. The lower wear rates reported secondary to more congruent bearings and may be a subject for future investigations. It may well be that even in mobile bearing unicompartmental knee replacements one to one the well aligned group will outperform the group left in residual varus.

Kinematic alignment may reliably achieve better ligament balance more often as shown by surgeons who tend to use mobile bearing prosthesis. It may be that as a strategy maintaining the soft tissue envelope in its original state is the ideal way to achieve soft tissue balance reliably at surgery. Surgeons have independently attempted to harmonise the rather diverging philosophies, one of not correcting alignment at the intraarticular level to achive good soft tissue balance and at the same time optimising overall alignment of the lower limb. There have been reports of correction of alignment achieved extraarticularly using an upper tibial osteotomy to achieve the precise desired alignment (Von Knoch 2012).

The present investigation has demonstrated the beneficial effect of correction of coronal alignment on dynamic loading. The above mentioned strategy of combining the osteotomy with replacement should be considered seriously as a method to reliably achieve soft tissue balance and alignment eventhough it adds to the complexity of the surgical procedure. It also opens up the possibility of offering unicompartmental knee replacements when the varus deformity is fixed or greater than 15^0, which would normally be considered a contraindication

10.2 Limitations and Directions for further research

This investigation has concentrated on the parameters that affect loading of the medial compartment of the knee on level walking. Although this reflects a large part of the loading episodes of the knee, it does not shed any light on loading in varying degrees of flexion as occurs in getting up from a low chair or in stair climbing. This might be an aspect for future research.

This investigation has recorded the improvement in clinical function scores following unicompartmental knee replacements, but it did not analyse the effect of loading on function scores. The number of knees in this investigation would have been inadequate for this purpose.

The effect of alignment on loading is very relevant in the discussions of mechanical and kinematic alignment in total knee replacements. Although the patient population who have total knee replacements are very different, inclusion of a further arm of total knee replacements might have been useful.

This investigation has revealed that correction of alignment has a significant impact on the loading of the medial compartment of the knee. This is postulated to increase the wear of the polyethylene liner and subsequently affect the survivorship of the unicompartmental knee prosthesis. The effect of PKAM and Add Imp on survivorship of unicompartmental knee replacement prosthesis might be an aspect for further research.

The effect of this increased loading on the different prosthetic designs namely on fixed bearing and mobile bearing prosthesis could be investigated, as the fixed bearing prosthesis has a lower surface area of contact between the metal and polyethylene components, compared to the mobile bearing prosthesis and would intuitively be more susceptible to increased loading. This clearly points to how ligament balance and hence kinematic alignment is vital in mobile bearing prosthesis, as lack of ligament balance can result in bearing dislocations which is a significant problem. In the case of fixed bearing prosthesis, ligament balance has a significant impact on function, but it might be more susceptible to variations in loading as they tend to be less congruent when compared to mobile bearings.

References

Al Zahrani KS, Bakheit AM, 2002. A study of the gait characteristics of patients with chronic osteoarthritis of the knee. *Disability & Rehabilitation*.24: 275–80.

Andrews M, Noyes FR, Hewett TE, Andriacchi TP, 1996. Lower limb alignment and foot angle are related to stance phase knee adduction in normal subjects: a critical analysis of the reliability of gait analysis data. *Journal of Orthopaedic Research.*14: 289–95.

Andriacchi TP, Mundermann A, Smith RL, Alexander EJ, Dyrby CO, Koo S, 2004. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Annals of Biomedical Engineering.*32: 447–57(cross ref)

Andriacchi TP, 1994. Dynamics of knee malalignment. *Orthopedic Clinics of North America*. 25: 395-403.

Andriacchi, T.P, Mundermann A, 2006. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Current Opinion in Rheumatology.* 18: 514–518.

Andriacchi TP, Galante J, 1982. The influence of total knee replacement design on walking. *Journal of Bone and Joint Surgery (Am)*. 64: 1328-35.

Ansari S, Newman JH, Ackroyd CE, 1997. St. Georg sled for medial compartment knee replacement. 461 arthroplasties followed for 4 - 17 years. *Acta Orthopaedica Scandinavica.* 68: 430-434.

Argenson JN, Chevrol-Benkeddache Y, Aubaniac JM, 2002. Modern unicompartmental knee arthroplasty with cement: a three to ten-year follow-up study. *Journal of Bone and Joint Surgery (Am)*. 84: 2235-2239.

Ashraf T, Newman JH, Evans RL, Ackroyd CE, 2002. Lateral unicompartmental knee replacement survivorship and clinical experience over 21 years. *Journal of Bone and Joint Surgery (Br).*84: 1126 - 1130.

Astephen JL, Deluzio KJ, Caldwell GE, Dunbar MJ, 2008. Biomechanical changes at the hip, knee, and ankle joints during gait are associated with knee osteoarthritis severity. *Journal of Orthopaedic Research.*26: 332-41.

Attfield S. Measurement of soft tissue balance during total knee replacement surgery : a retrospective and prospective evaluation. uk.bl.ethos.537622.

Bach CM, Nogler M, Steingruber IE, Ogon M, Wimmer C, Göbel G, Krismer M, 2002. Scoring systems in total knee arthroplasty. *Clinical Orthopaedics and Related Research.*399: 184 -196.

Baker R., Finney L, Orr J, 1999. A new approach to determine the hip rotation profile from clinical gait analysis data. *Human Movement Science*.18: 655-667. (cross ref)

Baker R., 2007. The history of gait analysis before the advent of modern computers. *Gait and Posture*.26: 331-42.

Baliunas AJ, Hurwitz DE, Ryals AB, Karrar A, Case JP, Block JA, Andriacchi TP, 2002 Increased knee joint loads during walking are present in subjects with knee osteoarthritis. *Osteoarthritis and Cartilage.*10: 573–579.

Banks SA, Markovich GD, Hodge WA, 1997. The mechanics of knee replacements during gait. In vivo fluoroscopic analysis of two designs. *American Journal of Knee Surgery*.10: 261-7.

Banks SA, Harman M K, Bellemans J, Hodge WA, 2003. Making sense of knee arthroplasty kinematics: news you can use. *Journal of Bone and Joint Surgery (Am)*. 85: 64-72.

Barrios JA, Crossley KM, Davis IS, 2010. Gait retraining to reduce the knee adduction moment through real-time visual feedback of dynamic knee alignment. *Journal of Biomechanics*.43: 2208–2213.

Barrios JA, Higginson JS, Royer TD, Davis IS, 2009. Static and dynamic correlates of the knee adduction moment in healthy knees ranging from normal to varus-aligned. *Clinical Biomechanics*. 24: 50–854.

Bartel DL, Bicknell VL, Wright TM, 1986. The effect of conformity, thickness, and material on stress in ultra-high molecular weight components for total joint replacement. *Journal of Bone and Joint Surgery (Am).*68: 1041-51.

Bayley KB, London MR, Grunkemeier GL, Lansky DJ, 1995. Measuring the success of treatment in patient terms. *Medical Care.*33: AS226–AS235.

Beaupre GS, Steven SS, Carter DR 2000. Mechanobiology in the development, maintenance and degeneration of articular cartilage. Journal of Rehabilitation Research Development 37:145-151.

Bell AL, Pedersen D R, Brand RA, 1990. A comparison of the accuracy of several hip center location prediction methods. *Journal of Biomechanics.*23: 617-21. (cross ref)

Benedetti M G, Catani F, Bilotta TW, Maracacci M, Mariani E, Giannini S,2003. Muscle activation pattern and gait biomechanics after total knee replacement. *Clinical Biomechanics.* 18: 871-6.

Bennell KL, Bowles KA, Wang Y, Cicuttini F, Davies-Tuck M, Hinman RS. 2011. Higher dynamic medial knee load predicts greater cartilage loss over 12 months in medial knee osteoarthritis. *Annals of the Rheumatic Diseases*.70: 1770-4.

Berend ME, Ritter MA, Meding JB, Faris PM, Keating EM, Redelman R, Faris GW, Davis KE, 2004. Tibial component failure mechanisms in total knee arthroplasty. *Clinical Orthopaedics and Related Research.*428: 26-34.

Bergenudd H, 1995. Porous-coated anatomic unicompartmental knee arthroplasty in osteoarthritis. A 3 to 9 year follow-up study. *Journal of Arthroplasty*.10: S8-S13.

Berger RA, Nedeff DD, Barden RM, Sheinkop MM, Jacobs JJ, Rosenberg AG, Galante JO, 1999. Unicompartmental knee arthroplasty. Clinical experience at 6- to 10-year followup. *Clinical Orthopaedics and Related Research.*367: 50-60.

Bert JM, Smith R, 1997. Failures of metal-backed unicompartmental arthroplasty. *The Knee*. 4: 41-48.

Birmingham TB, Hunt MA, Jones IC. 2007. Test -retest reliability of the peak knee adduction moment during walking in patients with medial compartment knee osteoarthritis. *Arthritis and Rheumatism.*57: 1012–7.

Borden L S, Perry J E, Davis BL, Owings TM, Grabiner MD, 1999. A biomechanical evaluation of one-stage vs two-stage bilateral knee arthroplasty patients. *Gait and Posture*.9: 24-30.

Borjesson M. Weidenhielm L. Mattsson E. Olsson E. 2005 Gait and clinical measurements in patients with knee osteoarthritis after surgery: a prospective 5-year follow-up study. *Knee.* 12:121-127.

Borjesson M. Weidenhielm L. Elfving B. Olsson E. 2007.Tests of walking ability at different speeds in patients with knee osteoarthritis. *Physiotherapy Research International.* 12:115-121.

Brandon SCE, Deluzio KJ, 2011. Robust Features of Knee Osteoarthritis in Joint Moments are Independent of Reference Frame Selection. *Clinical Biomechanics*.26: 65-70.

Braune, W.F., O, Über den Schwerpunkt des menschlichen körpes mit rücksicht auf die ausrüstung des Deutschen infanteristen, in Mathematisch-Psyphischen Classe. 1889, Sächsischen Gesellschaft der Wissenschaft: Leipzig (cross ref)

Brinkmann JR, Perry J, 1985. Rate and range of knee motion during ambulation in healthy and arthritic subjects. *Physical Therapy*.65: 1055-60.(cross ref)

Brouwer GM, van Tol AW, Bergink AP, Belo JN, Bernsen RM, Reijman M, Pols HA, Bierma-Zeinstra SM, 2007. Association between valgus and varus alignment and the development and progression of radiographic osteoarthritis of the knee. *Arthritis and Rheumatism.*56: 1204–1211.

Buechel FF, Pappas MJ, 1986. The New Jersey Low-Contact-Stress Knee Replacement System: Biomechanical rationale and review of the first 123 cemented cases. *Archives of Orthopaedic and Trauma Surgery.*105: 197 -204.

Buechel FF,2002. The LCS story. In: Hamelynck KJ, Stiehl JB, eds.LCS Mobile Bearing Knee Arthroplasty: a 25 Years Worldwide Review; Heidelberg, Germany: Springer: 19-25.

Callaghan JJ, Insall JN, Greenwald AS, Dennis DA, Komistek RD, Murray DW, 2000. Mobile-bearing knee replacement: Concepts and results. *Journal of Bone and Joint Surgery (Am)*.82: 1020 -1041.

Cappozzo A, Catani F, Della Croce U, Leardini A, 1995. Position and orientation in space of bones during movement: anatomoical frame definition and determination. *Clinical Biomechanics*.10: 171-178.

Cartier P, Deschamps G, 1977. Surgical principles of unicompartmental knee. Replacement. In: Cartier Ph, Epinette JA, Deschamps G, Hernigou Ph, eds. Unicompartmental knee arthroplasty. Paris: Expansion Scientifique Francaise. (cross ref)

Cartier P, Sanouiller JL, Grelsamer RP, 1996. Unicompartmental knee arthroplasty surgery: 10-year minimum follow-up period. *Journal of Arthroplasty.*11: 782-8.

Cerejo R, Dunlop DD, Cahue S, Channin D, Song J, Sharma L, 2002. The influence of alignment on risk of knee osteoarthritis progression according to baseline stage of disease. *Arthritis and Rheumatism*.46: 2632–2636.

Chakrabarty G, Newman JH, Ackroyd CE,1998. Revision of unicompartmental arthroplasty of the knee. Clinical and technical considerations. *Journal of Arthroplasty*.13: 191-196.

Chapple CM, Nicholson H, Baxter GD, Abbott JH, 2011. Patient Characteristics That Predict Progression of Knee Osteoarthritis: A Systematic Review of Prognostic Studies. *Arthritis Care & Research*.63: 1115–1125.

Chassin E P, Mikosz R P, Andriacchi TP, Rosenberg AG, 1996. Functional analysis of cemented medial unicompartmental knee arthroplasty. *Journal of Arthroplasty*.11: 553-9.

Chinn S, 1991. Repeatability and method comparison. *Thorax*.46: 454-456.

Cicuttini F, Ding C, Wluka A, Davis S, Ebeling PR, Jones G, 2005. Association of cartilage defects with loss of knee cartilage in healthy, middle-age adults: a prospective study. *Arthritis and Rheumatism*.52: 2033–2039.

Cole GK, Nigg BM, Ronsky JL, Yeadon MR, 1993. Application of the joint coordinate system to three-dimensional joint attitude and movement representation: a standardization proposal. *Journal of Biomechanical Engineering*.115: 344-349. (cross ref)

Collier MB, Eickmann TH, Sukezaki F, McAuley JP, Engh GA, 2006. Patient, implant and alignment factors associated with revision of medial compartment unicondylar arthroplasty. *J Arthroplasty.*21: 108 -115.

Cooke TD, Sled EA, Scudamore RA, 2007. Frontal plane knee alignment: a call for standardized measurement. *The Journal of Rheumatology*.34: 1796-801.

Cooke TDV, Price N, Fisher B, Hedden D, 1990. The inwardly pointing knee. An unrecognized problem of external rotational malalignment. *Clinical Orthopaedics and Related Research.*260: 56-60.

Cooper C, Snow S, McAlindon TE, Kellingray S, Stuart B, Coggon D, Dieppe PA, 2000. Risk factors for the incidence and progression of radiographic knee osteoarthritis. *Arthritis and Rheumatism*.43: 995-1000.

Davies AP, 2002. Rating systems for total knee replacement. *The Knee*.9: 261–266.

Davis, R.B. III, S. Ounpuu, D. Tyburski, J. R. Gage, 1991. A gait analysis data collection and reduction technique. *Human Movement Science.*10: 575-587.

Della Croce U, Leardini A, Chiari L, Cappozzo A, 2005. Human movement analysis using stereophotogrammetry. Part 4: assessment of anatomical landmark misplacement and its effects on joint kinematics. *Gait and Posture.*21: 226-237.

Deluzio KJ, Astephen JL, 2007. Biomechanical features of gait waveform data associated with knee osteoarthritis: An application of principal component analysis. *Gait and Posture.*25: 86-93.

Draper ER, Cable JM, Sanchez-Ballester J, Hunt N, Robinson JR, Strachan RK, 2002. Improvement in function after valgus bracing of the knee: an analysis of gait symmetry. *Journal of Bone and Joint Surgery (Br).*82: 1001-1005.

Elftman H, 1938. The Measurement of the External Force in Walking. *Science*.88: 152-153. (cross ref)

Emerson RH Jr, Hansborough T, Reitman RD, Rosenfeldt W, Higgins LL, 2002. Comparison of a mobile with a fixed bearing unicompartmental knee implant. *Clinical Orthopaedics and Related Research.*404: 62-70.

Emerson RH Jr, Higgins LL, 2008. Unicompartmental knee arthroplasty with the oxford prosthesis in patients with medial compartment arthritis. *Journal of Bone and Joint Surgery (Am)*. 90: 118-122.

Engelbrecht E, Siegel A, Rottger J, Buchholz HW, 1976. Statistics of total knee replacement: partial and total knee replacement, design St. Georg: a review of a 4-year observation. *Clinical Orthopaedics and Related Research.*120: 54-64.

Engelbrecht E, 1971. Sliding prosthesis, a partial prosthesis in destructive processes of the knee joint [in German]. *Chirurg*. 42: 510-514. (cross ref)

Engh GA, McAuley JP, 1999. Unicondylar arthroplasty: an option for high-demand patients with gonarthrosis. *Instructional Course Lectures*. 48: 143-148.

Engh GA, Ammeen DJ, 2001. Periprosthetic osteolysis with total knee arthroplasty. *Instructional Course Lectures*. 50: 391-398.

Fang DM, Ritter MA, Davis KE, 2009. Coronal alignment in total knee arthroplasty: just how important is it? *Journal of Arthroplasty*.4: 39 -43.

Felson DT, Zhang Y, Hannan MT, Naimark A, Weissman BN, Aliabadi P, Levy D, 1995. The incidence and natural history of knee osteoarthritis in the elderly: The Framingham Osteoarthritis Study. *Arthritis and Rheumatism*.38: 1500–1505.

Ferrari A, Benedetti MG, Pavan E, Frigo C, Bettinelli D, Rabuffetti M, Crenna P, Leardini A, 2008. Quantitative comparison of five current protocols in gait analysis. *Gait and Posture*. 28: 207-216.

Ferrigno G, Pedotti A, 1985. ELITE: a digital dedicated hardware system for movement analysis via real time TV signal processing. IEEE Transactions on Biomedical Engineering. 32: 943-50. (cross ref)

Fisher DA, Watts M, Davis KE, 2003. Implant position in knee surgery: a comparison of minimally invasive, open unicompartmental, and total knee arthroplasty. *Journal of Arthroplasty*.18 :2-8.

Fisher DS, Mundermann A, Andriacchi TP, 2004. Gait adaptations to recent footwear history: implication for the treatment of knee osteoarthritis. Transactions of Orthopaedic Research Society.50:88. (cross ref)

Fleiss J, Shrout P, 1978. Approximate interval estimation for a certain intraclass correlation coefficient. *Psychometrika*.43: 259-262.

Foroughi, N., Smith, R.M., Lange, A.K., Baker, M.K, 2010. Dynamic alignment and its association with knee adduction moment in medial knee osteoarthritis. *The Knee*.17: 210–216.

Fowler JL, Gie GA, Maceachern AG, 1991. Upper tibial valgus osteotomy using a dynamic external fixator. *Journal of Bone and Joint Surgery (Br*).73: 690-691.

FranzenA, InerotS, Hejderup SO, 1981; Variations in the composition of bovine hip articular cartilage with distance from articular surface. Biochemical Journal 195:535-543.

Fransen M, Crosbie J, Edmonds J, 1997. Reliability of gait measurements in people with osteoarthritis of the knee. *Physical Therapy*.77: 944- 953.

Fransen M, Crosbie J, Edmonds J, 2001. Physical therapy is effective for patients with osteoarthritis of the knee: a randomized controlled clinical trial. *Journal of Rheumatology*. 28:156–64.

Fransen M, McConnell S, Bell M, 2002. Therapeutic exercise for people with osteoarthritis of the hip or knee. A systematic review. *Journal of Rheumatology*.29: 1737–1745.

Fuchs S, Floren M, Skawara A, Tibesku CO, 2002. Quantitative gait analysis in unconstrained total knee arthroplasty patients. *International Journal of Rehabilitation Research*.25: 65-70.

Fuchs S. Tibesku CO. Frisse D. Laass H. Rosenbaum D. 2003. Quality of life and gait after unicondylar knee prosthesis are inferior to age-matched control subjects. *American Journal of Physical Medicine & Rehabilitation.* 82 :441-446, 2003.

Fuchs S. Rolauffs B. Plaumann T. Tibesku CO. Rosenbaum D.2005. Clinical and functional results after the rehabilitation period in minimally-invasive unicondylar knee arthroplasty patients. *Knee Surgery, Sports Traumatology, Arthroscopy*. 13 : 179-86.

Goh JC, 1993. Gait analysis study on patients with varus osteoarthrosis of the knee. *Clinical Orthopaedics and Related Research*.294: 223- 231.

Gok H, Ergin S, Yavuzer G, 2002. Kinetic and kinematic characteristics of gait in patients with medial knee arthrosis. *Acta Orthopaedica Scandinavica.*73: 647–52.

Goodfellow J, O'Connor JJ, 1992. The anterior cruciate ligament in knee arthroplasty. A risk-factor with unconstrained meniscal prostheses. *Clinical Orthopaedics and Related Research.*276: 245-252.

Goodfellow J, O'Connor JJ, 1978. The mechanics of the knee and prosthesis design. *Journal of Bone and Joint Surgery (Br*) 60: 358-69.

Goodfellow JW, Kershaw CJ, Benson MK, O'Connor JJ, 1988. The Oxford Knee for unicompartmental osteoarthritis. The first 103 cases. *Journal of Bone and Joint Surgery (Br*). 70: 692-701.

Goodfellow JW, O'Connor JJ, 1986. Clinical results of the Oxford knee. Surface arthroplasty of the tibiofemoral joint with a meniscal bearing prosthesis. *Clinical Orthopaedics and Related Research.*205: 21-42.

Goodman S, Lidgren L, 1992. Polyethylene wear in knee arthroplasty. A review. *Acta Orthopaedica Scandinavica*.63: 358-364.

Grood ES, 1983. A joint co-ordinate system for the clinical description of three-dimensional motions: Application to the knee. *Journal of Biomechanical Engineering.*105: 136 - 144. (cross ref)

Gulati AA, Chau RR, Simpson DJ, Dodd CA, Gill HS, Murray DW, 2009. The effect of leg alignment on the outcome of unicompartmental knee replacement. *The Knee.*16: 196-199.

Gunston FH, 1971. Polycentric knee arthroplasty. Prosthetic simulation of normal knee movement. *Journal of Bone and Joint Surgery (Br*).53: 272-277.

Guo M, Axe MJ, Manal K, 2007. The influence of foot progression angle on the knee adduction moment during walking and stair climbing in pain free individuals with knee osteoarthritis. *Gait and Posture.*26: 436–441.

Haapala JJ,Arokoski PP, Hyttinen MM, Lammi M, Tammi M, Kovanen V, Helminen HJ, Kiviranta I, 1999. Remobilization does not fully restore immobilization induced articular cartilage atrophy. *Clinical Orthopaedics and Related Research*.362: 218–229.

Harrison MM, Cooke TD, Fisher SB, Griffin MP, 1994. Patterns of knee arthrosis and patellar subluxation. *Clinical Orthopaedics and Related Research.*309: 56-63.

Heck DA, Marmor L, Gibson A, Rougraff BT, 1993. Unicompartmental knee arthroplasty. A multicenter investigation with long-term follow-up evaluation. *Clinical Orthopaedics and Related Research.*286: 154-159.

Henriksen M, Simonsen EB, Alkjaer T, Lund H, Graven-Nielsen T, Danneskiold-Samsøe, Bliddal H, 2006. Increased Joint loads during walking. Consequence of pain relief in knee osteoarthritis. *The Knee*.13: 445 – 450.

Hernigou P, Deschamps G, 2004. Alignment influences wear in the knee after medial unicompartmental arthroplasty. *Clinical Orthopaedics and Related Research.*423: 161-5.

Hilding MB, Lanshammar H, Ryd L, 1996. Knee joint loading and tibial component loosening. RSA and gait analysis in 45 osteoarthritic patients before and after TKA. *Journal of Bone and Joint Surgery. (Br*).78: 66-73.

Hilding MB, Ryd L, Toksvig-Larsen S, Mann A, Stenstrom A, 1999. Gait affects tibial component fixation. *Journal of Arthroplasty*.14: 589-93.

Hodge WA, Chandler HP, 1992. Unicompartmental knee replacement: a comparison of constrained and unconstrained designs. *Journal of Bone and Joint Surgery (Am*).74: 877-883.

Hsu RW, Himeno S, Coventry MB, Chao EY, 1990. Normal axial alignment of the lower extremity and load-bearing distribution at the knee. *Clinical Orthopaedics and Related Research*.255: 215-27.

Huang MH, Lin YS, Yang RC, Lee CL, 2003. A comparison of various therapeutic exercises on the functional status of patients with knee osteoarthritis. *Seminars in Arthritis and Rheumatism.*32: 398–406.

Hungerford D, 1987: Cement disease. *Clinical Orthopaedics and Related Research*.225: 192- 206.

Hunt MA, Birmingham TB, Jenkyn TR, Giffin JR, Jones IC, 2008. Measures of frontal plane lower limb alignment obtained from static radiographs and dynamic gait analysis. *Gait and Posture.*27: 635–640.

Hurwitz DE, Ryals AB, Case JP, Block JA, Andriacchi TP, 2002. The knee adduction moment during gait in subjects with knee osteoarthritis is more closely correlated with static alignment than radiographic disease severity, toe out angle and pain. *Journal of Orthopaedic Research.*20: 101–7.

Hurwitz DE, Sumner DR, Andriacchi TP, Sugar DA, 1998. Dynamic knee loads during gait predict proximal tibial bone distribution. *Journal of Biomechanics*.31: 423–30.

Insall J, Aglietti P, 1980. A five-to-seven-year follow-up of unicondylar arthroplasty. *Journal of Bone and Joint Surgery (Am*).62: 1239 - 42.

Insall JN, Ranawat CS, Aglietti P, Shine J, 1976. A comparison of four models of total knee-replacement prostheses. *Journal of Bone and Joint Surgery (Am*).58: 754–765.

Issa SN, Dunlop D, Chang A, Song J, Prasad PV, Guermazi A, Peterfy C, Cahue S, Marshall M, Kapoor D, Hayes K, Sharma L, 2007. Full-limb and knee radiography assessments of varus-valgus alignment and their relationship to osteoarthritis disease features by magnetic resonance imaging. *Arthritis and Rheumatism*.57: 398-406.

Jackson BD, Teichtahl AJ, Morris ME, Wluka AE, Davis SR, Cicuttini FM, 2004. The effect of the knee adduction moment on tibial cartilage volume and bone size in healthy women. *Rheumatology*.43: 311–314.

Janse AJ, Gemke RJBJ, Uiterwaal CSPM, Tweel I, Kimpen JL, Sinnema G, 2004. Quality of life: patients and doctors don't always agree: a meta-analysis. *Journal of Clinical Epidemiology*.57: 653–661. (cross ref)

Jarvenpaa J, Kettunen J, Miettinen H, Kruger H, 2009. The clinical outcome of revision knee replacement after unicompartmental knee arthroplasty versus primary total knee arthroplasty: 8 -17 years follow-up study of 49 patients. *International Orthopaedics*.34: 649-655.

Jeffery RS, Morris RW, Denham RA, 1991. Coronal alignment after total knee replacement. *Journal of Bone and Joint Surgery (Br)*.73: 709 – 714.

Jenkyn TR, Hunt MA, Jones IC, Giffin JR, Birmingham TB, 2008. Toe-out gait in patients with knee osteoarthritis partially transforms external knee adduction moment into flexion moment during early stance phase of gait: A tri-planar kinetic mechanism. *Journal of Biomechanics*.41: 276–283.

John J, Mauffrey CM, May PC, 2011. Unicompartmental knee replacements with Miller – Galante prosthesis. 2 to 16 year follow up of a single surgeon series. *International Orthopaedics*.35: 507-13.

John J, Kuiper JH, May PC (2009). Age at follow-up and mechanical axis are good predictors of function after unicompartmental knee arthroplasty. An analysis of patients over 17 years follow-up. *Acta Orthopaedica Belgica.* 75: 45-50.

Jurvelin J, I. Kiviranta, M. Tammi, and J. H. Helminen, 1986. Softening of canine articular cartilage after immobilization of the knee joint. *Clinical Orthopaedics and Related Research*.207: 246–252.

Kadaba MP, Ramakrishnan HK, Wootten ME, Gainey J, Gorton G, Cochran GV, 1989. Repeatability of kinematic, kinetic, and electromyographic data in normal adult gait. *Journal of Orthopaedic Research*.7: 849–60.

Kaufman KR, Hughes C, Morrey BF, Morrey M, An K, 2001. Gait characteristics of patients with knee osteoarthritis. *Journal of Biomechanics.*34: 907- 915.

Kean CO, Hinman RS, Bowles KA, Cicuttini F, Davies-Tuck M, Bennell KL, 2012. Comparison of peak knee adduction moment and knee adduction moment impulse in distinguishing between severities of knee osteoarthritis. *Clinical Biomechanics.* 27: 520-3.

Keene G, Simpson D, Kalairajah Y, 2006. Limb alignment in computer-assisted minimally invasive unicompartmental knee replacement. *Journal of Bone and Joint Surgery (Br*). 88: 44-8.

Kennedy WR, White RP, 1987. Unicompartmental arthroplasty of the knee. Postoperative alignment and its influence on overall results. *Clinical Orthopaedics and Related Research.*221: 278 -295.

Kerrigan DC, Karvosky ME, Lelas JL, Riley PO, 2003. Men's shoes and knee joint torques relevant to the development and progression of knee osteoarthritis. *Journal of Rheumatology.*30: 529–33.

Keys GW, 1999. Reduced invasive approach for Oxford II medial unicompartmental knee replacement; preliminary study. *The Knee.*6: 193-196.

Kirtley C, 2006. Clinical Gait Analysis: Theory & Practice. Oxford, Elsevier.

Konig A, Scheidler M, Rader C, Eulert J, 1997. The need for a dual rating system in total knee arthroplasty. *Clinical Orthopaedics and Related Research.*345: 161–167.

Kozinn S, Scott R. Current concepts review, 1989. Unicondylar knee arthroplasty. *Journal of Bone and Joint Surgery (Am*).71: 145 – 51.

Kraus VB, Vail TP, Worrell T, McDaniel G, 2005. A comparative assessment of alignment angle of the knee by radiographic and physical examination methods. *Arthritis and Rheumatism.*52: 1730-1735.

Krishnan R, Park S Eckstein F 2003; Inhomogenous cartilage properties enhance superficial interstitial fluid support and frictional properties but do not provide a homogenous state of stress.*Journal of Biomechanical Engineering* 125: 569-577.

Lafortune MA, Cavanagh PR, Sommer PJ, Kalenak A, 1992. Three-dimensional kinematics of the human knee during walking. *Journal of Biomechanics*.25: 347–357.

Landry SC, McKean KA, Hubley-Kozey CL, Stanish WD, Deluzio KJ, 2007. Knee biomechanics of moderate OA patients measured during gait at a self-selected and fast walking speed. *Journal of Biomechanics*.40: 1754-61.

Larsson SE, Larsson S, Lundkvist S, 1988. Unicompartmental knee arthroplasty: a prospective consecutive series following for six to 11 years. *Clinical Orthopaedics and Related Research*.232: 174-81.

Laskin R.S, 1978. Unicompartmental tibiofemoral resurfacing arthroplasty. *Journal of Bone and Joint Surgery (Am)*.60: 182-6.

Leardini A, Chiari L, Della Croce U, Cappozzo A, 2005. Human movement analysis using stereophotogrammetry. Part 3. Soft tissue artifact assessment and compensation. *Gait and Posture*.21: 212-225.

Leardini A, Sawacha Z, Paolini G, Ingrosso S, Nativo R, Benedetti MG, 2007. A new anatomically based protocol for gait analysis in children. *Gait and Posture*.26: 560– 571.

Ledingham J, Regan M, Jones A, Doherty M, 1993. Radiographic patterns and associations of osteoarthritis of the knee in patients referred to hospital. *Annals of Rheumatic Diseases*.52: 520-6.

Lee MS, Trinidade MC, Ikenoue T 2002: Effects of shear stress on nitric oxide and matrix protein gene expression in human osteoarthritic chondrocytes in vitro. *Journal of Orthopaedic Research*. 20: 556-561.

Lelas JL, Merriman GJ, Riley PO, 2003. Predicting peak kinematic and kinetic parameters from gait speed. *Gait and Posture* 17: 106–112.

Lementowski P, Zelicof S, 2008. Obesity and osteoarthritis. *American Journal of Orthopedics*.37: 148 - 151.

Levine WN, Ozuna RM, Scott RD, Thornhill TS, 1996. Conversion of failed modern unicompartmental arthroplasty to total knee arthroplasty. *Journal of Arthroplasty*.11: 797-801.

Light LH, McLellan GE, Klenerman L, 1980. Skeletal transients on heel strike in normal walking with different footwear. *Journal of Biomechanics.*13: 477–80. (cross ref)

Lindstrand A, Stenstrom A, Lewold S, 1992. Multicenter study of unicompartmental knee revision. PCA, Marmor, and St Georg compared in 3,777 cases of arthrosis. *Acta Orthopaedica Scandinavica.*63: 256-259.

Lundberg A, 1996. On the use of bone and skin markers in kinematics research. *Human Movement Science.*15: 411-422.

Luscombe KL, Lim J, Jones PW, White SH, 2007. Minimally invasive Oxford medial unicompartmental knee arthroplasty. A note of caution! *International Orthopaedics.*31: 321 – 324.

Lynn S K, Reid SM, Costigan PA, 2007. The influence of gait pattern on signs of knee osteoarthritis in older adults over a 5-11 year follow-up period: A case study analysis. *The Knee.*14: 22-28.

Lynn SK, Kajaks T, Costigan PA, 2008. The effect of internal and external foot rotation on the adduction moment and lateral-medial shear force at the knee during gait. *Journal of Sport Science Medicine.*11: 444–451.

Lyons MC, MacDonald SJ, Somerville LE, Naudie DD, McCalden RW, 2012. Unicompartmental Versus Total Knee Arthroplasty Database Analysis. Is There a Winner? *Clinical Orthopaedics and Related Research*.470: 84–90.

Marmor L, 1973. The modular knee. *Clinical Orthopaedics and Related Research*.94: 242-248

Marmor L, 1988. Unicompartmental knee arthroplasty: ten- to 13-year follow-up study. *Clinical Orthopaedics and Related Research*.226: 14-20.

Martimbianco ALC, Calabrese FR, Luiz, Iha LAN, Petrilli M, Neto OL, Filho MC, 2012 Reliability of the "American Knee Society Score" (AKSS). *Acta Ortopédica Brasileira.*20(1): 34 – 38.

MacIntosh DL, Hunter GA, 1972. The use of the hemiarthroplasty prosthesis for advanced osteoarthritis and rheumatoid arthritis of the knee. *Journal of Bone and Joint Surgery (Br)*.54: 244-255.

Mackinnon J, Young S, Baily RA, 1988. The St Georg sled for unicompartmental replacement of the knee. A prospective study of 115 cases. *Journal of Bone and Joint Surgery (Br)*.70: 217 – 223.

Manal, K, McClay I, Richards J, Galinat B, Stanhope S, 2002. Knee moment profiles during walking: errors due to soft tissue movement of the shank and the influence of the reference coordinate system. *Gait and Posture.*15: 10-17.

Manca M, Leardini A, Cavazza S, Ferraresi G, Marchi P, Zanaga E, Benedetti MG, 2010. Repeatability of a new protocol for gait analysis in adult subjects. *Gait and Posture.*32: 282– 284.

Manetta J, Franz LH, Moon C, Perell KL, Fang M, 2002. Comparison of hip and knee muscle moments in subjects with and without knee pain. *Gait and Posture.*16: 249-54.

Mäntyselkä P, Kumpusalo E, Ahonen R, Takala J, 2001. Patients' versus general practitioners' assessments of pain intensity in primary care patients with non-cancer pain. *British Journal of General Practice.*51: 995–997.

Manzotti A, Confalonieri N, Pullen C, 2007. Unicompartmental versus computer-assisted total knee replacement for medial compartment knee arthritis: a matched paired study. *International Orthopaedics.*31: 315- 319.

Marx RG, Grimm P, Lillemoe KA, Robertson CM, Ayeni OR, Lyman S, Bogner EA, Pavlov H, 2011. Reliability of lower extremity alignment measurement using radiographs and PACS. *Knee Surgery, Sports Traumatology, Arthroscopy*.19: 1693-8.

Mattsson E. Olsson E. Brostrom LA.1990. Assessment of walking before and after unicompartmental knee arthroplasty. A comparison of different methods. *Scandinavian Journal of Rehabilitation Medicine.* 22: 45-50.

McClelland JA, Webster KE, Feller JA,2007. Gait analysis of patients following total knee replacement: a systematic review. *The Knee*.14: 253-63.

McGinley J.L., Baker R., Wolfe R., Morris M.E, 2009. The reliability of three-dimensional kinematic gait measurements: A systematic review. *Gait and Posture*.29: 360–369.

McKean KA, Landry SC, Hubley-Kozey CL, Dunbar MJ, Stanish WD, Deluzio KJ, 2007. Gender differences exist in osteoarthritic gait. *Clinical Biomechanics*.22: 400- 409.

Mercier N, Wimsey S, Saragaglia D, 2010. Long-term clinical results of the Oxford medial unicompartmental knee arthroplasty. *International Orthopaedics*.34: 1137-1143.

Messier SP, Loeser RF, Hoover JL, Semble EL, Wise CM, 1992. Osteoarthritis of the knee: Effects on gait, strength, and flexibility. *Archives of Physical Medicine and Rehabilitation*.73: 29-36.

Michael AR, Boyle J, Mihalko WM, Phillips MJ, Krackow KA, Bayers-Thering M, 2007. Reliability of Measuring Long-standing Lower Extremity Radiographs. *Orthopedics*.30: 299 – 303.

Miyazaki T, Wada M, Kawahara H, Sato M, Baba H, Shimada S, 2002. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Annals of the Rheumatic Diseases*.61: 617–622.

MochidaY, Duarte WR, TanzawaH 2003. Decorin modulates matrix mineralization invitro. Biochemical and Biophysical Research Communications 305:6-9 (cross ref)

Moreland JR, Bassett LW, Hanker GJ, 1987. Radiographic analysis of the axial alignment of the lower extremity. *Journal of Bone and Joint Surgery (Br*).69: 745–749.

Moreland JR, 1988. Mechanisms of failure in total knee arthroplasty. *Clinical Orthopaedics and Related Research*.226: 49-64.

Muir H, Bullough P, Maroudas A 1970: The distribution of collagen in human articular cartilage with some of its physiological implications. *Journal of Bone and Joint Surgery.* 52: 554-563, Mullaji AB, Shetty GM, Kanna R, 2011. Postoperative limb alignment and its determinants after minimally invasive Oxford medial unicompartmental knee arthroplasty. *Journal of Arthroplasty*.26: 919-25.

Mundermann A, Dyrby CO, Andriacchi TP, 2005. Secondary gait changes in patients with medial compartment knee osteoarthritis: increased load at the ankle, knee, and hip during walking. *Arthritis and Rheumatism*.52: 2835–44.

Murphy L, Schwartz TA, Helmick CG, Renner JB, Tudor G, Koch G, Dragomir A, Kalsbeek WD, Luta G, Jordan JM, 2008. Lifetime risk of symptomatic knee osteoarthritis. Arthritis and Rheumatism.59: 1207–13.

Muybridge E, 1878. The science of the horse's motions. *Scientific American*.39: 241 (cross ref)

Nagura T, Matsumoto H, Kiriyama Y, Chaudhari A, Andriacchi TP, 2006. Tibiofemoral joint contact force in deep knee flexion and its consideration in knee osteoarthritis and joint replacement. *Journal of Applied Biomechanics*.22: 305–313.

O'Connor JJ, Shercliff TL, Biden E, Goodfellow JW, 1989. The geometry of the knee in the sagittal plane. *Proceedings of Institution of Mechanical Engineers*.203: 223-233. (cross ref)

O'Connor JJ, Goodfellow JW, 1996. Theory and practice of meniscal knee replacement: design against wear. *Proceedings of Institution of Mechanical Engineers*.210: 217-222. (cross ref)

Olney SJ. Gait. In: Levangie P, Norkin C, editors .2005. Joint Structure and Function: A Comprehensive Analysis. 4th ed. Philadelphia, PA: F.A. Davis Company.

Oswald MH, Jakob RP, Schneider E, Hoogewoud HM, 1993. Radiological analysis of normal axial alignment of femur and tibia in view of total knee arthroplasty. *Journal of Arthroplasty*.8: 419-426.

Otterness IG, Eskra JD, Bliven ML, Shay AK, Pelletier JP, Milici AJ, 1998. Exercise protects against articular cartilage degeneration in the hamster. *Arthritis and Rheumatism*.41: 2068–2076.

Padgett DE, Stern SH, Insall JN, 1991. Revision total knee arthroplasty for failed unicompartmental replacement. *Journal of Bone and Joint Surgery (Am*).73: 186-190.

Paley D, Pfeil J, 2000. Principles of deformity correction around the knee. *Orthopade.*29: 18-38

Parratte S, Pagnano MW, Trousdale RT, Berry DJ, 2010. Effect of postoperative mechanical axis alignment on the fifteen-year survival of modern, cemented total knee replacements. *Journal of Bone and Joint Surgery (Am*). 92: 2143- 2149.

Patil S, Colwell CW, Ezzet KA, D'Lima DD, 2005. Can normal knee kinematics be restored with unicompartmental knee replacement? *Journal of Bone and Joint Surgery (Am*) 87: 332-8.

Pennington DW, Swienckowski JJ, Lutes WB, Drake GN, 2006. Lateral unicompartmental knee arthroplasty: survivorship and technical considerations at an average follow-up of 12.4 years. *Journal of Arthroplasty.*21: 13 -17.

Perkins TR, Gunckle W, 2002. Unicompartmental knee arthroplasty: 3- to 10-year results in a community hospital setting. *Journal of Arthroplasty.*17: 293 – 297.

Perry J, 1992. Gait Analysis: Normal and Pathological Function, New Jersey, SLACK Inc.

Price AJ, Webb J, Topf H, Dodd CA, Goodfellow JW, Murray DW, 2001. Rapid recovery after Oxford unicompartmental arthroplasty through a short incision. *Journal of Arthroplasty.*16: 970-976.

Psychoyios V, Crawford RW, O’ Connor JJ, Murray DW, 1998. Wear of congruent meniscal bearings in unicompartmental knee arthroplasty: a retrieval study of 16 specimens. *Journal of Bone and Joint Surgery (Br*).80: 976-982.

Queen RM, Gross MT, Liu HY. Repeatability of lower extremity kinetics and kinematics for standardized and self-selected running speeds. *Gait and Posture*.23: 282–287.

Rajasekhar C, Das S, Smith A, 2004. Unicompartmental knee arthroplasty. 2- to 12-year results in a community hospital. *Journal of Bone and Joint Surgery (Am*).86: 983–985.

Ramakrishnan HK, Kadaba MP, 1991. On the estimation of joint kinematics during gait. *Journal of Biomechanics*.24: 969–977.

Ramsey DK, Wretenberg PF, Benoit DL, Lamontagne M, Nemeth G, 2003. Methodological concerns using intra-cortical pins to measure tibiofemoral kinematics. *Knee Surgery Sports Traumatology Arthroscopy*.11: 344- 349.

Repicci JA, Eberle RW, 1999. Minimally invasive surgical technique for unicondylar knee arthroplasty. *Journal of the Southern Orthopaedic Association.*8: 20-27.

Ridgeway SR, McAuley JP, Ammeen DJ, Engh GA 2002. The effect of alignment of the knee on the outcome of unicompartmental knee replacement. *Journal of Bone and Joint Surgery (Br).*84: 351-5.

Riebel GD, Werner FW, Ayers DC, Bromka J, Murray DG, 1995. Early failure of the femoral component in unicompartmental knee arthroplasty. *Journal of Arthroplasty*.10: 615-621.

Robinson BJ, Rees JL, Price AJ, Beard DJ, Murray DM. 2002. A kinematic study of lateral unicompartmental arthroplasty. *The Knee*.9: 237-40.

Romanowski M, Repicci J, 2002. Eight year follow up on minimally invasive unicondylar arthroplasty. Paper presented at: Meeting of the American Academy of Orthopaedic Surgeons. Dallas, Texas. (cross ref)

Saari T, Tranberg R, Zugner R, Uvehammer J, Karrholm J, 2005. Changed gait pattern in patients with total knee arthroplasty. *Acta orthopaedica Scandinavica.*76: 253-60.

Sandell LJ, Towler DA, 2002: Transcription of bone and cartilage genes.*Current Opinion in Orthopaedics*, 13:375-381.

Sanfridsson J, Ryd L, Svahn G, Friden T, Jonsson K, 2001. Radiographic measurement of femorotibial rotation in weight-bearing. The influence of flexion and extension in the knee on the extensor mechanism and angles of the lower extremity in a healthy population. *Acta Radiologica.*42: 207-17.

Saragaglia D, Estour G, Nemer C, Colle PE, 2009. Revision of 33 unicompartmental knee prostheses using total knee arthroplasty: strategy and results. *International Orthopaedics*.33: 969- 974.

Schai PA, Suh JT, Thornhill TS, Scott RD, 1998. Unicompartmental knee arthroplasty in middle-aged patients: a 2- to 6-year follow-up evaluation. *Journal of Arthroplasty*.13: 365-372.

Schipplein OD, Andriacchi TP, 1991. Interaction between active and passive knee stabilizers during level walking. *Journal of Orthopaedic Research*.9: 113- 119.

Schmitt LC, Rudolph KS, 2007. Influences on knee movement strategies during walking in persons with medial knee osteoarthritis. *Arthritis and Rheumatism*.57: 1018–1026.

Schwartz MH, Trost JP, Wervey RA, 2004. Measurement and management of errors in quantitative gait data. *Gait and Posture*. 20: 196–203.

Scott RD, Cobb AG, McQueary FG, Thornhill TS, 1991. Unicompartmental knee arthroplasty: eight to twelve year follow-up evaluation with survivorship analysis. *Clinical Orthopaedics and Related Research.*271: 96-100.

Scott RD, Joyce MJ, Ewald FC, Thomas WH. McKeever, 1985. metallic hemiarthroplasty of the knee in unicompartmental degenerative arthritis. Long term clinical follow-up and current indications.. *Journal of Bone and Joint Surgery (Am*).67: 203-207.

Scuderi GR, Bourne RB, Noble PC, Benjamin JB, Lonner JH, Scott WN, 2012. The New Knee Society Knee Scoring System. *Clinical Orthopaedics and Related Research.*470: 3–19.

Selvik, G, 1989. Roentgen stereophotogrammetry. A method for the study of the kinematics of the skeletal system. *Acta Orthopaedica Scandinavica*. (Suppl) 232: 1-51. (cross ref)

Sharma L, Hurwitz DE, Thonar EJ, Sum JA, Lenz ME, Dunlop DD, Schnitzer TJ, Kirwan-Mellis G, Andriacchi TP, 1998. Knee adduction moment, serum hyaluronan level, and disease severity in medial tibiofemoral osteoarthritis. *Arthritis and Rheumatism.*41: 1233-40.

Sharma L, Eckstein F, Song J, Guermazi A, Prasad P, Kapoor D, Cahue S, Marshall M, Hudelmaier M, Dunlop D, 2008. Relationship of meniscal damage, meniscal extrusion, malalignment, and joint laxity to subsequent cartilage loss in osteoarthritic knees. *Arthritis and Rheumatism.*58: 1716- 1726.

Sharma L, Song J, Felson DT, Cahue S, Shamiyeh E, Dunlop DD, 2001. The role of knee alignment in disease progression and functional decline in knee osteoarthritis. *The Journal of the American Medical Association.*286: 188-95.

Sharma L, Kapoor D, Issa S. 2006. Epidemiology of osteoarthritis: an update. *Current Opinion in Rheumatology.*18: 147–156.

Shelburne KB, Torry MR, Pandy MG, 2006. Contributions of muscles, ligaments, and the ground-reaction force to tibiofemoral joint loading during normal gait. *Journal of Orthopaedic Research.*24: 1983–1990.

Shull PB, Shultz R, Silder A, Dragoo JL, Besier TF, Cutkosky MR, Delp SL, 2013. Toe-in gait reduces the first peak knee adduction moment in patients with medial compartment knee osteoarthritis. *Journal of Biomechanics*.46: 122-8.

Simon SR, Treishmann HW, Burdett RG, Ewald FC, Sledge CB, 1983. Quantitative gait analysis after total knee arthroplasty for monarticular degenerative arthritis. *Journal of Bone and Joint Surgery (Am)*.65: 605-13.

Sled EA, Cooke D, Sheehy L, Lam M, Costigan P, Nevitt M, Torner JC, Lewis CE, Sharma L. Reliability of Lower Limb Frontal Plane Alignment Measures Obtained with the Use of a Computer Program and Electronic Tools World Congress on Osteoarthritis. Fort Lauderdale, FL. Dec. 2007. Available at: http://works.bepress.com/elizabeth_sled/11

Smith AJ, Lloyd DG, Wood DJ, 2004. Pre-surgery knee joint loading patterns during walking predict the presence and severity of anterior knee pain after total knee arthroplasty. *Journal of Orthopaedic Research*.22: 260- 266.

Springer BD, Scott RD, Sah AP, Carrington R, 2006. McKeever hemiarthroplasty of the knee in patients less than sixty years old. *Journal of Bone and Joint Surgery (Am*).88: 366-371.

Squire MW, Callaghan JJ, Goetz DD, Sullivan PM, Johnston RC, 1999. Unicompartmental knee replacement. A minimum 15 year followup study. *Clinical Orthopaedics and Related Research.*367: 61-72.

Stauffer RN, Chao EY, Gyory AN, 1977. Biomechanical gait analysis of the diseased knee joint. *Clinical Orthopaedics and Related Research.*126: 246-55. (cross ref)

Steele RG, Hutabarat S, Evans RL, Ackroyd CE, Newman JH, 2006. Survivorship of the St Georg Sled medial unicompartmental knee replacement beyond ten years. *Journal of Bone and Joint Surgery (Am*).88: 1164- 1168.

Steinwender G, Saraph V, Scheiber S, Zwick EB, Uitz C, Hackl K,2000. Intrasubject repeatability of gait analysis data in normal and spastic children. Clinical Biomechanics.15: 134–139.

Stiehl JB, Komistek RD, Dennis DA, Paxson RD, 1995. Fluoroscopic analysis of kinematics after posteriorcriciate- retaining knee arthroplasty. *Journal of Bone and Joint Surgery (Am*). 77: 884-895.

Suggs JF, Li G, Park SE, Steffensmeier S, Rubash HE, Freiberg AA, 2004. Function of the anterior cruciate ligament after unicompartmental knee arthroplasty: an in vitro robotic study. *Journal of Arthroplasty.*19: 224-229.

Sundaramurthy S, Mao JJ. 2005. Modulation of Endochondral development of the distal femoral condyle by mechanical loading. Journal of Orthopaedic Research 24:229-241.

Sutherland DH, 2002. The evolution of clinical gait analysis. *Gait and Posture*.16: 159-79.

Taylor WR, Heller MO, Bergmann G, Duda GN, 2004. Tibiofemoral loading during human gait and stair climbing. *Journal of Orthopaedic Research..*22: 625–632

Tetsworth K, Paley D, 1994. Malalignment and degenerative arthropathy. *Orthopedic Clinics of North America*.25: 367-77.

The knee society score. The Knee Society. Outcomes assessment. Available at: https:\\www.kneesociety.org/web/outcomes.html.

Thorp LE, Sumner DR, Block JA, Moisio KC, Shott S, Wimmer MA, 2006. Knee joint loading differs in individuals with mild compared with moderate medial knee osteoarthritis. *Arthritis and Rheumatism.*54: 3842-3429.

Thorp LE, Sumner DR, Wimmer MA, Block JA, 2007. Relationship between pain and medial knee joint loading in mild radiographic knee osteoarthritis. *Arthritis and Rheumatism.*57: 1254-60.

Thorp LE, Wimmer MA, Block JA, Moisio KC, Shott S, Goker B, Sumner DR, 2006. Bone mineral density in the proximal tibia varies as a function of static alignment and knee adduction angular momentum in individuals with medial knee osteoarthritis. *Bone.*39: 1116-22.

Vanwanseele F, Eckstein H, Knecht E, St¨ussi, Spaepen A, 2002. Knee cartilage of spinal cord-injured patients displays progressive thinning in the absence of normal joint loading and movement. *Arthritis and Rheumatism*.46: 2073–2078.

Von Knoch F, Manner H, Harder L, von Knoch M, Preiss S. 2012. Combined unicondylar knee arthroplasty and high tibial osteotomy for isolated medial compartmental knee arthritis with juxta-articular coronal deformity. *Swiss Med Wkly*. 142 (Suppl 193):134.

Vince KG, Insall JN, Kelly MA. The total condylar prosthesis: 10- to 12-year results of a cemented knee replacement. *Journal of Bone and Joint Surgery (Am*).71: 793-797.

Wada M, Maezawa Y, Baba H, Shimada S, Sasaki S, Nose Y, 2001. Relationships among bone mineral densities, static alignment and dynamic load in patients with medial compartment knee osteoarthritis. *Rheumatology.*40: 499–505.

Wakeling JM, Liphardt AM, Nigg BM, 2003. Muscle activity reduces soft-tissue resonance at heel-strike during walking. *Journal of Biomechanics.*36: 1761–9.

Walter JP, D'Lima DD, Colwell CW Jr, Fregly BJ, 2010 .Decreased knee adduction moment does not guarantee decreased medial contact force during gait. *Clinical Orthopaedics and Related Research.*28: 1348- 1354.

Webster KE. Wittwer JE. Feller JA. 2003. Quantitative gait analysis after medial unicompartmental knee arthroplasty for osteoarthritis. *Journal of Arthroplasty*. 18: 751-9.

White SH, Ludkowski PF, Goodfellow JW. Anteromedial osteoarthritis of the knee. *Journal of Bone and Joint Surgery (Br)*.73: 582-586.

Whittaker JP, Naudie DD, McAuley JP, McCalden RW, MacDonald SJ, Bourne RB, 2010 . Does bearing design influence midterm survivorship of unicompartmental arthroplasty? *Clinical Orthopaedics and Related Research.*468: 73–81.

Winter DA, 2005. Biomechanics and Motor Control of Human Movement. Third ed. John Wiley & Sons, Inc.

Woltring HJ, 1994. 3-D attitude representation of human joints: a standardization proposal. *Journal of Biomechanics*.27: 1399-414. (cross ref)

Wright JG, Young NL. The patient-specific index: asking patients what they want. *Journal of Bone and Joint Surgery (Am*). 79: 974–983.

Wylde V, Learmonth I, Potter A, Bettinson K, Lingard E. Patient-reported outcomes after fixed- versus mobile-bearing total knee replacement: a multi-centre randomisedcontrolled trial using the Kinemax total knee replacement. *Journal of Bone and Joint Surgery (Br*). 90: 1172–1179.

Zatsiorsky V,1998. Kinematics of Human Motion. ISBN 0-88011-676- 5, pg 9-10. (cross ref)

Zeni JA, Higginson JS, 2009. Differences in gait parameters between healthy subjects and persons with moderate and severe knee osteoarthritis: A result of altered walking speed? *Clinical Biomechanics*.24: 372-378.

Zeni JA, Higginson JS, 2009. Dynamic knee joint stiffness in subjects with a progressive increase in severity of knee osteoarthritis. *Clinical Biomechanics.*24: 366-371.

Zhang W, Doherty M, Peat G, Bierma-Zeinstra MA, Arden NK, Bresnihan B, Herrero-Beaumont G, Kirschner S, Leeb BF, Lohmander LS, Mazières B, Pavelka K, Punzi L, So

AK, Tuncer T, Watt I, Bijlsma JW, 2010. EULAR evidence-based recommendations for the diagnosis of knee osteoarthritis. *Annals of Rheumatic Diseases.*69: 483–9.

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Appendix A

STAFFORDSHIRE UNIVERSITY

+ Version 1.5

Date; 10/07/10

CONSENT FORM

Title of Project: Assessment of Medial compartment arthritis

Name of Researcher: J John **Please initial box**

1. I confirm that I have read and understand the information sheet for the above study and have had the opportunity to ask questions. ☐

2. I understand that my participation is voluntary and that I am free to withdraw at anytime without giving any reason, without my medical care or legal rights being affected. ☐

3. I understand that IF NECESSARY sections of any of my medical notes may be looked at by responsible individuals from this research group or from regulatory authorities where it is relevant to my taking part in research. I give permission for these individuals to have access to my records. ☐

4. I agree to take part in the above study. ☐

______________________	______________	__________________
Name of Patient	Date	Signature
______________________	______________	__________________
Name of Person taking consent (if different from researcher)	Date	Signature
______________________	______________	__________________
Researcher	Date	Signature

Derby Hospitals NHS
NHS Foundation Trust

Appendix B

Royal Derby Hospital
Uttoxeter Road
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STAFFORDSHIRE
UNIVERSITY

Patient Information Sheet

Study Title: Assessment of medial compartment arthritis

Version 1.7

Date: 10/07/2010

My name is J John. I am one of the Orthopaedic trainees and I am currently proposing to undertake a research project in the area of medial compartment arthritis. The team involved in this project includes **Mr. S. Attfield, Clinical Scientist, Mr. R Straw, Consultant Orthopaedic Surgeon, Mr. SAW. Pickering, Consultant Orthopaedic Surgeon, TJ Wilton Consultant Orthopaedic Surgeon and Prof N. Chockalingam.**

We would like to invite you to participate in this study to clarify the role of articulating surfaces in the regulation of weight bearing. We would like to study the gait of all participants for this purpose. The nature of the study and gait analysis are detailed below. We are undertaking this study in patients who are undergoing unicompartmental knee replacements.

You would also be requested to fill two questionnaires, with questions regarding your activity and function levels.

Feel free to ask us if there is anything that is not clear from the information provided.

What is the purpose of the study?

Medial compartment arthritis of the knee may be treated in different ways. Although previous studies have identified some of the mechanics involved, movement analysis will improve our understanding of medial compartment arthritis and may help to find improvements in the treatment of this condition. More over the study will shed light on the role of the joint surfaces in regulating the load that passes through the knee while weight bearing.

Why have I been invited?

All patients with medial compartment arthritis under the care of **Mr. R Straw, Mr. SAW. Pickering and TJ Wilton** will be invited to participate in this project.

Do I have to take part?

It is your decision whether you wish to take part in this study. We will describe the study and go through this information sheet, which we will then give to you. We will then ask you to sign a consent form to show you have agreed to take part. You are free to withdraw at any time, without giving a reason. We would like to clarify at the outset that participation in the study or refusal to do so would not in any way affect the surgical treatment that you are about to undergo

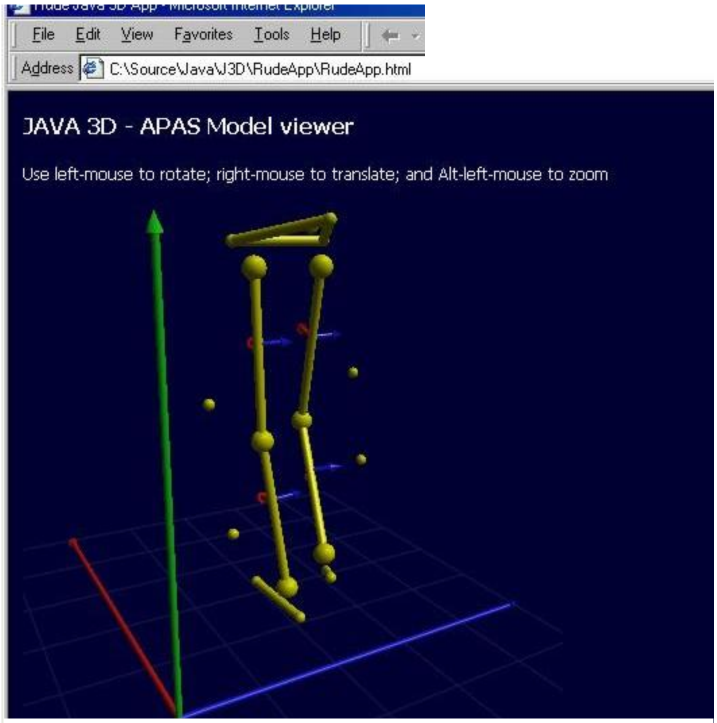
What will happen to me if I take part?

Each participant would be involved in the research for up to a year and each participant would have to meet the research team twice. These visits will last approximately 30 minutes including clarification of any questions you may have. We would try to avoid any delay while waiting for the gait analysis, although occasionally this might happen.We will ask a few questions. Reflective markers resembling a small ball will be placed on a few positions on your body and you will be filmed during normal walking in the laboratory.We will place small reflective balls on your body in predetermined positions on your legs. (Picture 1)

Picture 1: Picture of a subject with reflective markers undergoing gait analysis

You will then be asked to walk 5-6 times across the laboratory. Then we will record your walking pattern using a few cameras as you walk across the laboratory with the reflective markers.

This recording will then be analysed with the help of a computer. The computer measures various movements of the markers and calculates the joint angles to build up a picture of the total movement. During the tests you are required to wear underwear or swimming clothing so that the reflective markers placed on the body may be seen clearly by the cameras during the movement. Although your walking pattern will be recorded in your underwear as shown in Picture 1, the data analysis will involve the relative position of the reflective markers attached onto your body and not your body segments (Picture 2). The data analysis will not show pictures of the person, but just lines connecting the markers. The room is heated, but you can bring a tracksuit to keep warm as well.



Picture 2: Image used for analysis (Note: the body parts are not evident)

Applet started.

Where will the study take place?

The study will take place at the gait analysis laboratory. Our laboratory is situated in the London community Hospital (Old Derby Royal Infirmary)

What are the risks?

The testing procedures are totally safe and there are no known risks involved.

Will I benefit from the study?

You will not immediately benefit by taking part in this project but we hope to obtain a greater understanding of medial compartment arthritis that in the long term will help to improve treatment.

You will not "own" the results of the study and will not benefit from taking part.

Will my medical details be kept secret?

Your name and address will be kept separately from your medical details and will not be entered on to the study computer. The information we obtain will be treated confidentially and will not be passed on to others. We will follow ethical and legal practice and all information about you will be handled in confidence

Can I choose whether to enter the study or not and can I withdraw from the study if I change my mind?

The decision to take part in this study is entirely yours and will not affect any other treatment.

You can withdraw from the study at any time with out giving a reason.

Will I get reimbursement for the travel to the hospital?

No, the researcher is a student and is not in a position to personally reimburse the travel expenses. We would like to reiterate that participation is entirely voluntary.

Does this study involve Ionising radiation?

No. This study does not involve ionising radiation.

What can I do if I have a complaint?

If you have complaint about anything at all, you can follow the normal procedure for complaints in the NHS and contact the patient advice liaison services (PALS). The PALS office is situated inside the entrance to the Main Hospital at RDH opposite Costa coffee

The PALS office is open 9.00 am to 5.00 pm, Monday to Thursday and 9.00 am to 4.30 pm on Friday.

If you have any questions about this study you can contact one of the study team. The names and addresses are as below:

Mr. J John

Gait laboratory,
London road Community Hospital
London Road
Derby
DE 1 2QY

Telephone: 01332 340131(4793)

Mr. Steve Attfield

Gait laboratory,
London road Community Hospital
London Road
Derby
DE 1 2QY

Telephone: 01332 340131(4793)

Thank you very much for taking time to read the information sheet.

Appendix C

North Staffordshire Local Research Ethics Committee
Mellor House
Corporation Street
Stafford
Staffordshire
ST16 3SR

Telephone: 01785 257888 ext 5941

09 October 2008

Mr Joby John
SPR in Orthopaedics
Derbyshire Royal Infirmary
London Road
Derby
DE1 2QY

Dear Mr John

Full title of study:	**Investigate the contribution of articular surface in the regulation of adduction moments in the knee - using data collected from patients undergoing medial unicompartmental knee replacements**
REC reference number:	**08/H1204/85**

Thank you for your letter of 28 June 2008, responding to the Committee's request for further information on the above research and submitting revised documentation.

The further information was considered at the meeting of the Committee held on 08 October 2008. A list of the members who were present at the meeting is attached.

Confirmation of ethical opinion

On behalf of the Committee, I am pleased to confirm a favourable ethical opinion for the above research on the basis described in the application form, protocol and supporting documentation as revised, subject to the conditions specified below.

Ethical review of research sites

The Committee has designated this study as exempt from site-specific assessment (SSA). The favourable opinion for the study applies to all sites involved in the research. There is no requirement for other Local Research Ethics Committees to be informed or SSA to be carried out at each site.

Conditions of the favourable opinion

The favourable opinion is subject to the following conditions being met prior to the start of the study.

Management permission or approval must be obtained from each host organisation prior to the start of the study at the site concerned.

Management permission at NHS sites ("R&D approval") should be obtained from the relevant care organisation(s) in accordance with NHS research governance arrangements. Guidance on applying for NHS permission is available in the Integrated Research Application System or at http://www.rdforum.nhs.uk.

Approved documents

The final list of documents reviewed and approved by the Committee is as follows:

Document	*Version*	*Date*	
Response to Request for Further Information		28 June 2008	
CV of supervisor			
Participant Consent Form	1.3	28 February 2008	
Peer Review		19 March 2008	
Letter from Sponsor		16 May 2007	
Summary/Synopsis	1.2	28 February 2008	
Covering Letter		31 March 2008	
Protocol	1.2	28 February 2008	
Investigator CV			
Application		31 March 2008	
Letter from Dr Jim Radcliffe re peer review		18 September 2008	
Participant Information Sheet	1.6	28 August 2008	
Covering Letter			
Response to Request for Further Information			

Statement of compliance

The Committee is constituted in accordance with the Governance Arrangements for Research Ethics Committees (July 2001) and complies fully with the Standard Operating Procedures for Research Ethics Committees in the UK.

After ethical review

Now that you have completed the application process please visit the National Research Ethics Website > After Review

You are invited to give your view of the service that you have received from the National Research Ethics Service and the application procedure. If you wish to make your views known please use the feedback form available on the website.

The attached document "After ethical review – guidance for researchers" gives detailed guidance on reporting requirements for studies with a favourable opinion, including:

- Notifying substantial amendments
- Progress and safety reports
- Notifying the end of the study

The NRES website also provides guidance on these topics, which is updated in the light of changes in reporting requirements or procedures.

We would also like to inform you that we consult regularly with stakeholders to improve our service. If you would like to join our Reference Group please email referencegroup@nres.npsa.nhs.uk.

08/H1204/85	**Please quote this number on all correspondence**

With the Committee's best wishes for the success of this project

Yours sincerely

Dr Mark Gunning
Vice Chair

Email: Janet.Clarke@ssh-tr.nhs.uk

Enclosures:	*List of names and professions of members who were present at the meeting and those who submitted written comments* "After ethical review – guidance for researchers"
Copy to:	Dr D Clements, R&D Manager, UHNS Paul Richards, Deputy Vice Chancellor, Staffordshire University, Beaconside, Stafford, ST18 0AD Dr N Chockalingham, Reader in Clinical Biomechanics, Staffordshire University, Leek Road, Stoke-on-Trent, ST4 2DF

North Staffordshire Local Research Ethics Committee

Attendance at Committee meeting on 08 October 2008

Committee Members:

Name	*Profession*	*Present*	*Notes*	
Mrs Margaret Bennett	Senior Public Relations Officer	No		
Miss Nicola Brooks	Solicitor	No		
Professor Chris Cullen	Consultant Psychologist	Yes		
Mr Michael Dale	Engineering Manager (Retired)	Yes		
Dr Deborah Fox	Lecturer in Nursing	No		
Mrs Shirley Goldstraw	Lecturer in Nursing	No		
Dr Mark Gunning	Cardiologist	Yes		
Dr Melissa Hubbard	Consultant Paediatrician	Yes		
Dr David Hunter	Professor of Ethics	Yes		
Dr Kelvin Jordan	Statistician	Yes		
Dr Jackie-Ann Kilding	Community Paediatrician	No		
Mr Peter Proctor	Pottery Manager (Retired)	No		
Dr Mark Shapley	General Practitioner	Yes		
Professor Monica Spiteri	Consultant Physician	Yes		
Dr Elaine Thomas	Statistician	No		
Mrs Susan Thomson	Pharmacy Manager	Yes		
Mr Dewi Williams	Lecturer in Law	No		

Also in attendance:

Name	*Position (or reason for attending)*	
Mrs Barbara Cannings	Coordinator	

Appendix D

DHFT Research & Innovation Department
ISSUED
22 SEP 2010

Derby Hospitals **NHS**
NHS Foundation Trust

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Research and Development Office

TRUST APPROVAL LETTER

Mr J John
SpR in Orthopaedics
Hand Unit
Royal Derby Hospitals
Uttoxeter Road
Derby
DE22 3NE

Dear Mr John

Re: Gait analysis in patients undergoing unicompartmental knee replacements (Ref. DHRD/2010/050).

Further to Research Ethics Committee approval for the above study, I am pleased to confirm Trust management approval for you to proceed in accordance with the agreed protocol, the Trust's financial procedures for research & development and the Research Governance Framework (which includes the Data Protection Act 1998 and the Health & Safety at Work Act 1974).

Please supply the following to Dr Teresa Grieve, Assistant Director of R&D, Derby Hospitals NHS Foundation Trust (Teresa.Grieve@derbyhospitals.nhs.uk):

- the actual start and end dates of this study (**before the study commences**).
- details of any publications arising from this research project.
- a final report and a report every six months if the study duration is greater than six months.
- notification of any adverse event or changes to the protocol or if the trial is abandoned.

Please note that approval for this study is dependent on full compliance with all of the above conditions.

I would like to take this opportunity to wish you every success with this study.

Yours sincerely,

Prof. Richard Donnelly MD, PhD, FRCP, FRACP
Director of Research & Development

Appendix E

Modified Knee Society Score

Functional Scoring

Walking	50
Unlimited	40
>10 blocks	30
5-10 blocks	20
<5 blocks	10
Housebound	0
Stairs	
Normal up & down	50
Normal up,down with rail	40
Up & down with rail	30
Up with rail; unable down	15
Unable	0
Functional Deductions	
Cane	-5
Two canes	-10
Crutches or walker	-20
Other	20

Knee Score
Knee Findings
Pain 50 (Maximum)

Walking	
None	35
Mild or occasional	30
Moderate	15
Severe	0
Stairs	
None	15
Mild or occasional	10
Moderate	5
Severe	0

R.O.M. 25 (Maximum)

8º= 1 point

Stability 25 (Maximum)

Medial/Lateral	
0-5 mm	15
5-10 mm	10

> 10 mm	5

Anterior/Posterior

0-5 mm	10
5-10 mm	8
> 10 mm	5

Deductions

Extension lag

None	0
<4 degrees	-2
5-10 degrees	-5
>11 degrees	-10

Flexion Contracture

< 5 degrees	0
6-10 degrees	-3
11-20 degrees	-5
> 20 degrees	-10

Malalignment

5-10 degrees	0
(5º = -2 points)	

Pain at rest

Mild	-5
Moderate	-10
Severe	-15
Symptomatic plus objective	0

Knee Score 100 (Maximum) =

Appendix F

Summary of Tests for normality of data

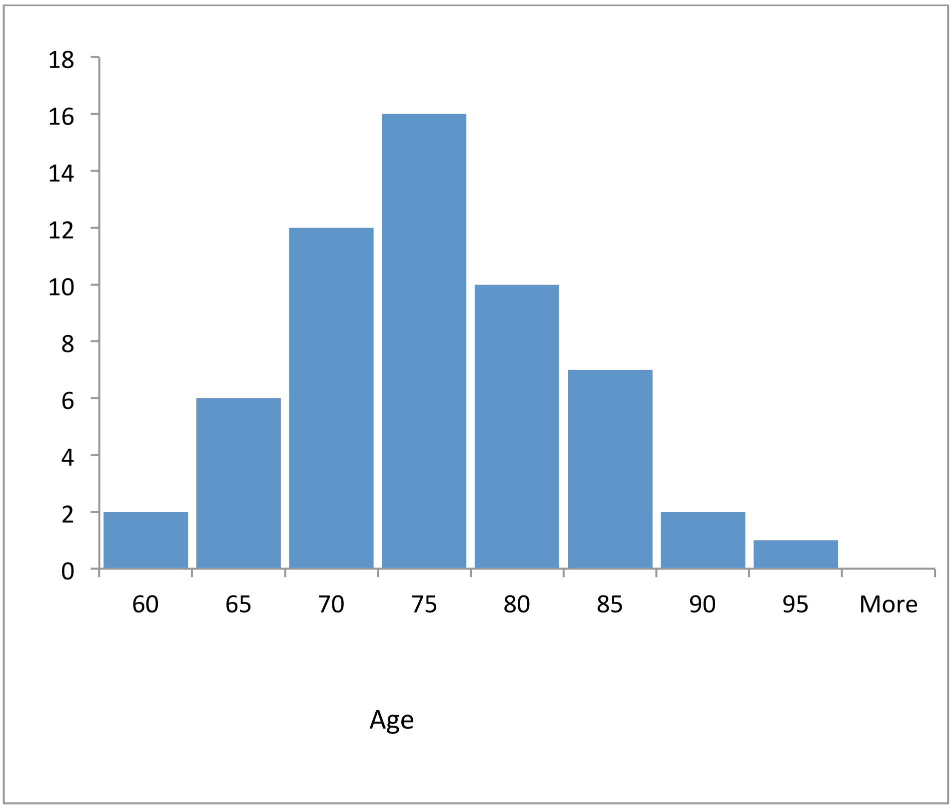
Study 1

Tests of Normality

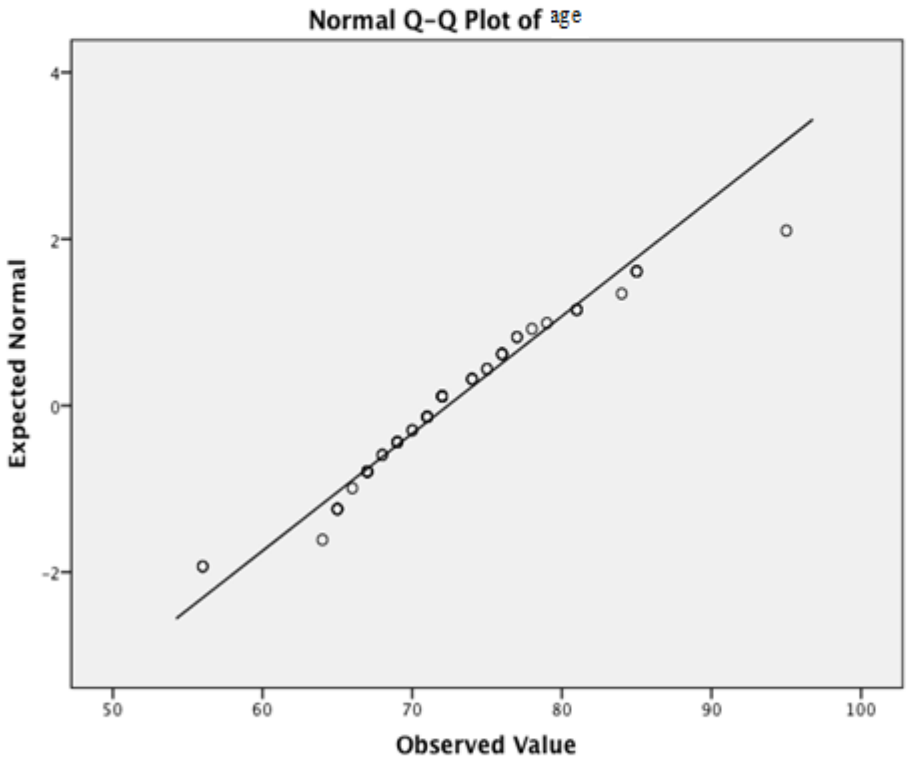
	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Age	.121	55	.052	.962	55	.081
Angle	.151	55	.063	.967	55	.141
Zone	.253	55	.080	.890	55	.090

a. Lilliefors Significance Correction

Histogram for Age

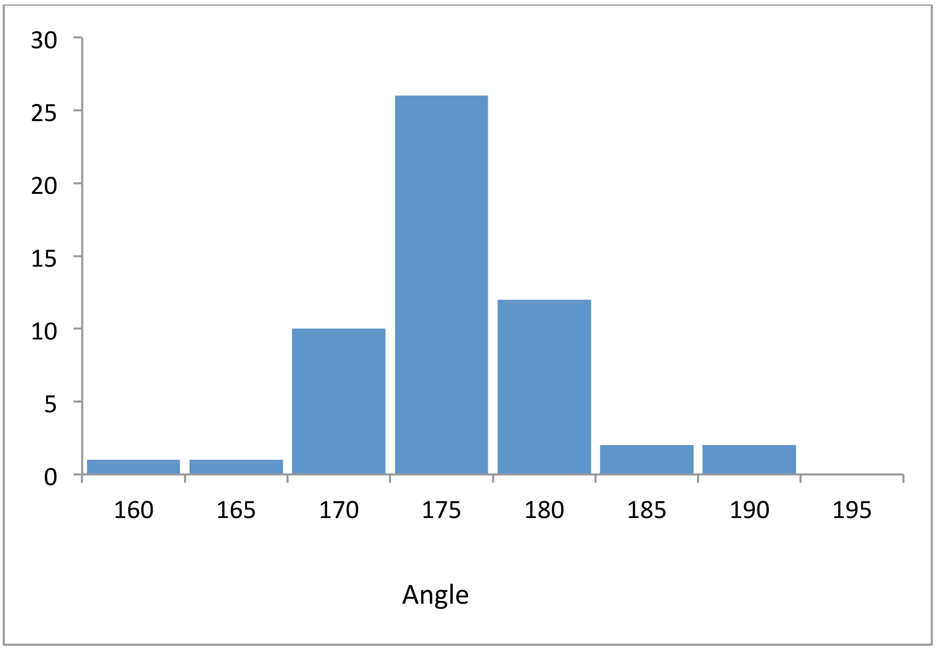


q-q plot for age

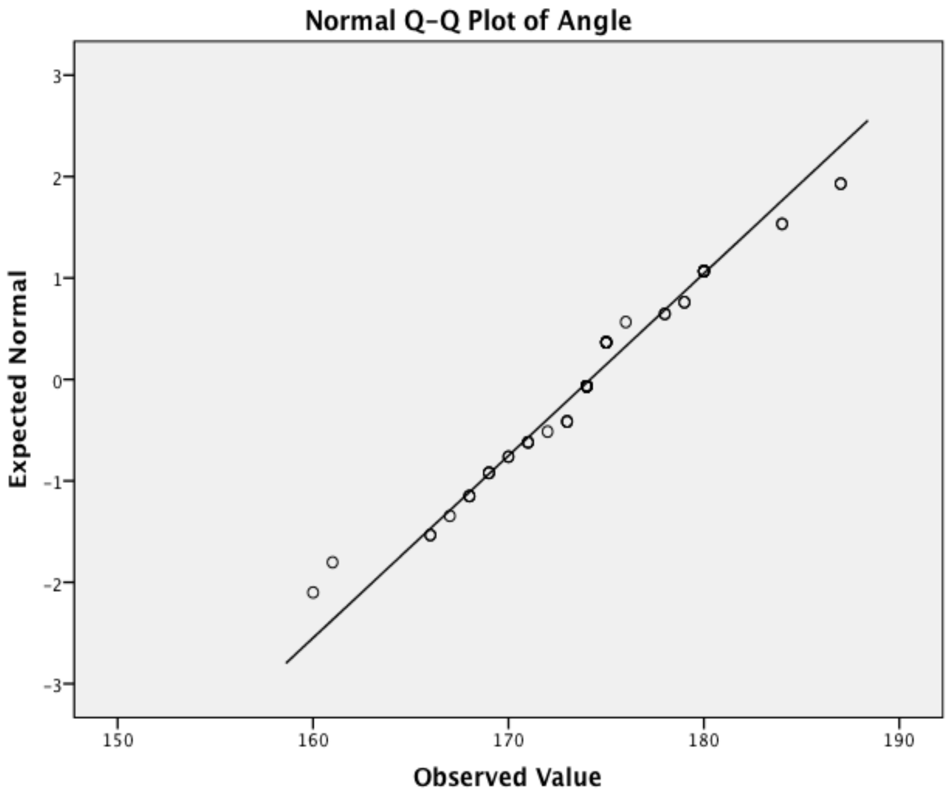


Angular data study1

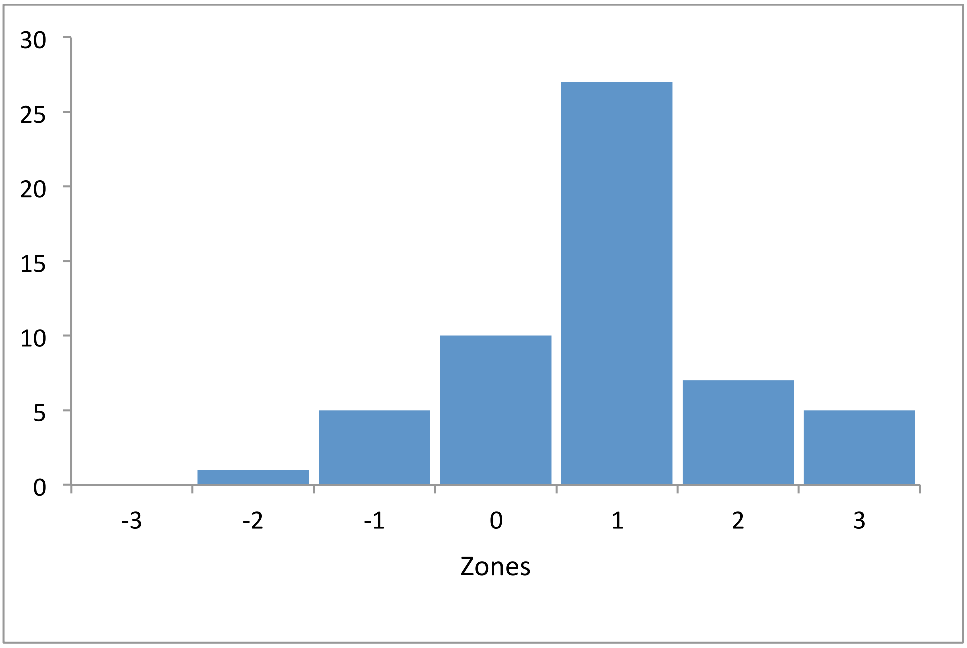
Histogram for Angle



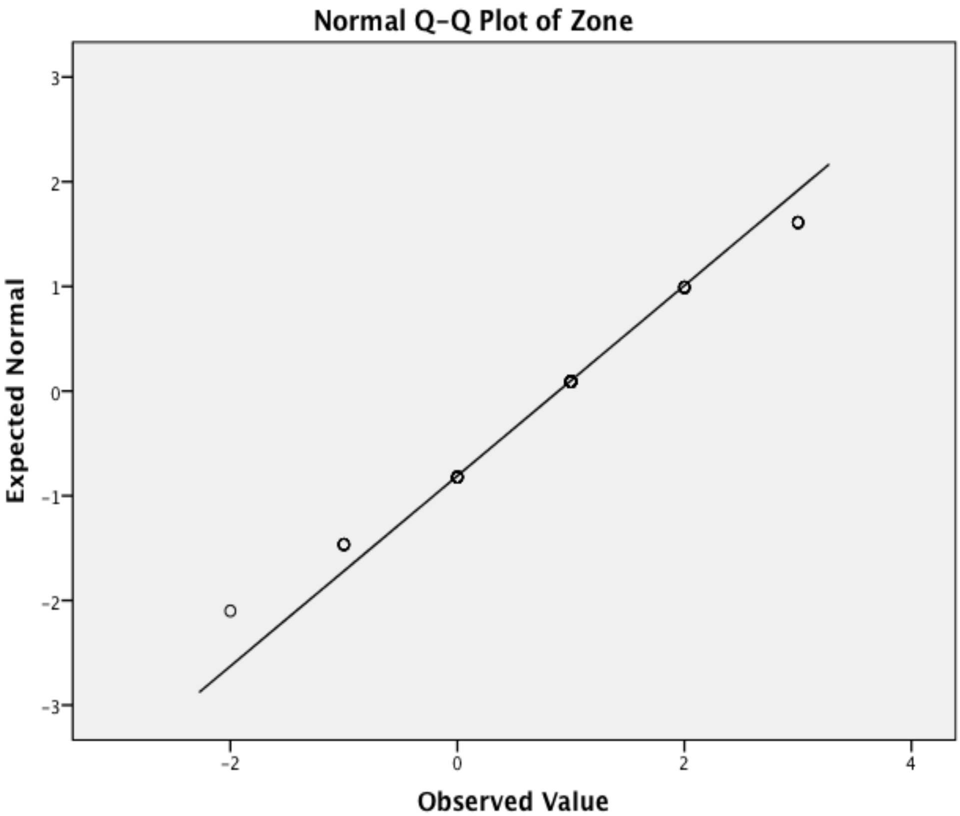
q-q plot for Angle



Histogram for zone



q-q plot for zone



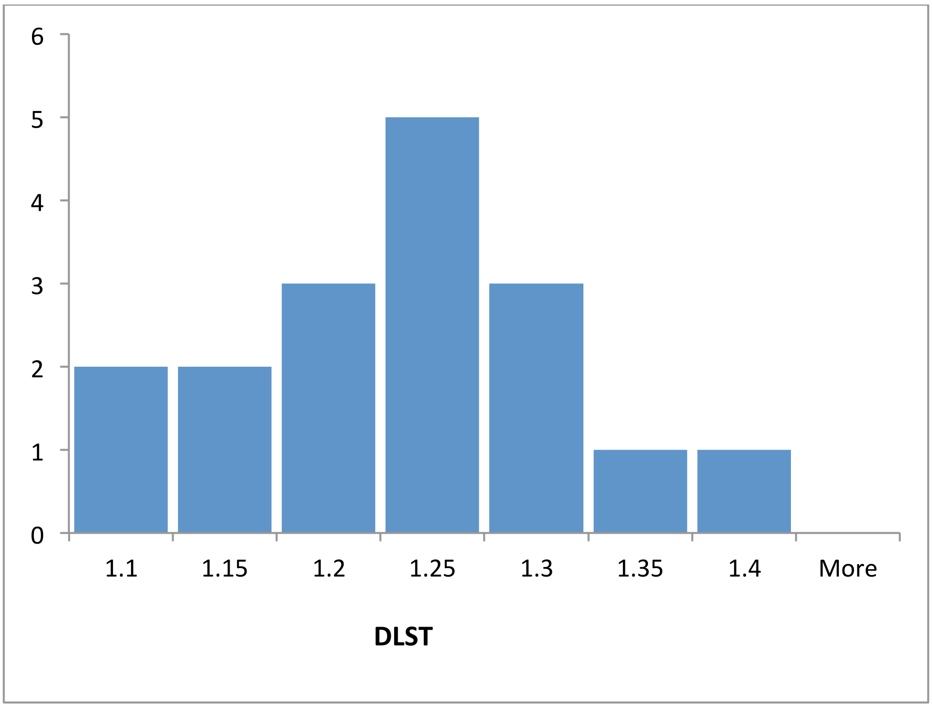
Summary of Normality testing for Study 2

Temporo spatial parameters

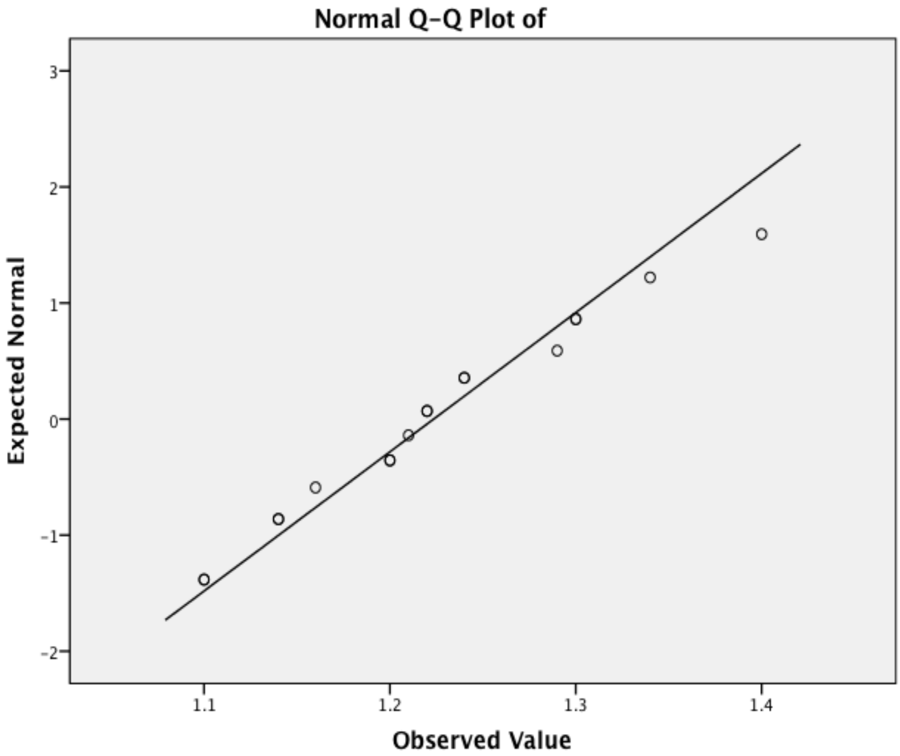
Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	Df	Sig.
DLST	.128	17	.200*	.965	17	.724
Velocity	.186	17	.123	.868	17	.021
Cadence	.136	17	.200*	.955	17	.540

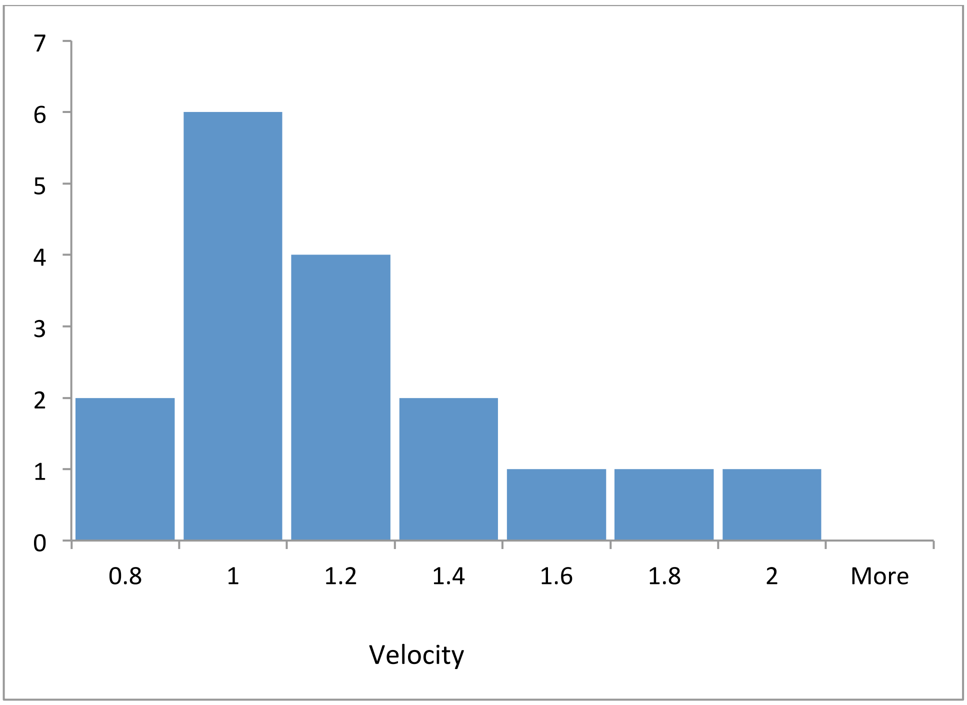
Histogram for DLST



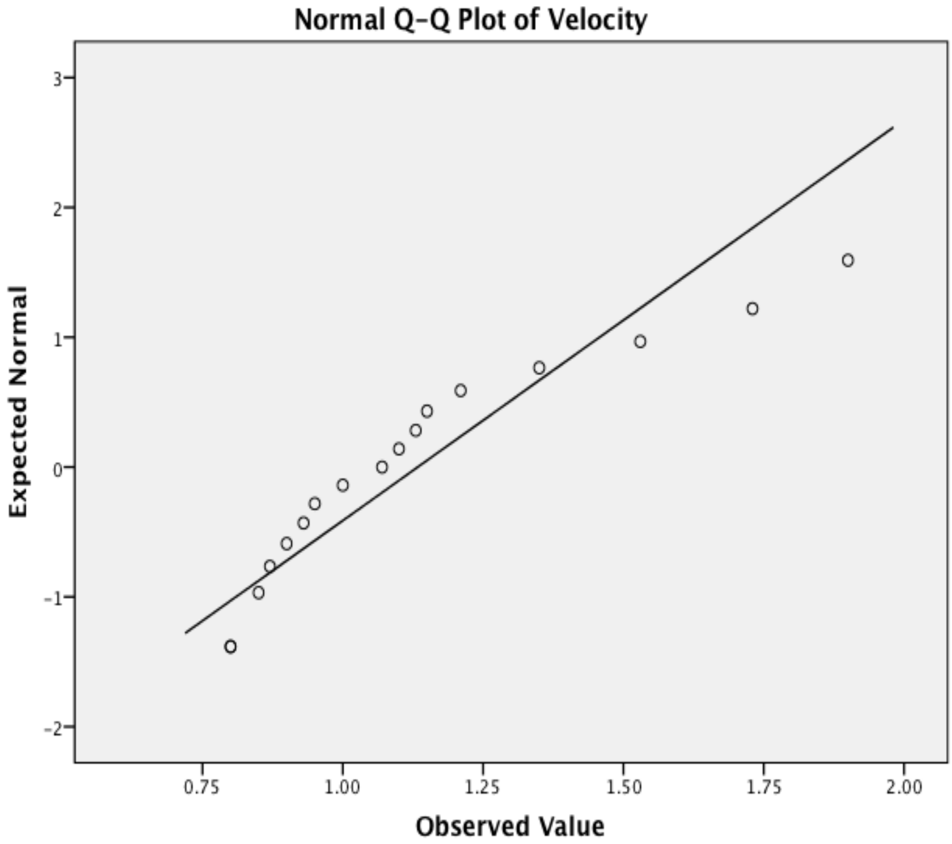
q-q plot for DLST



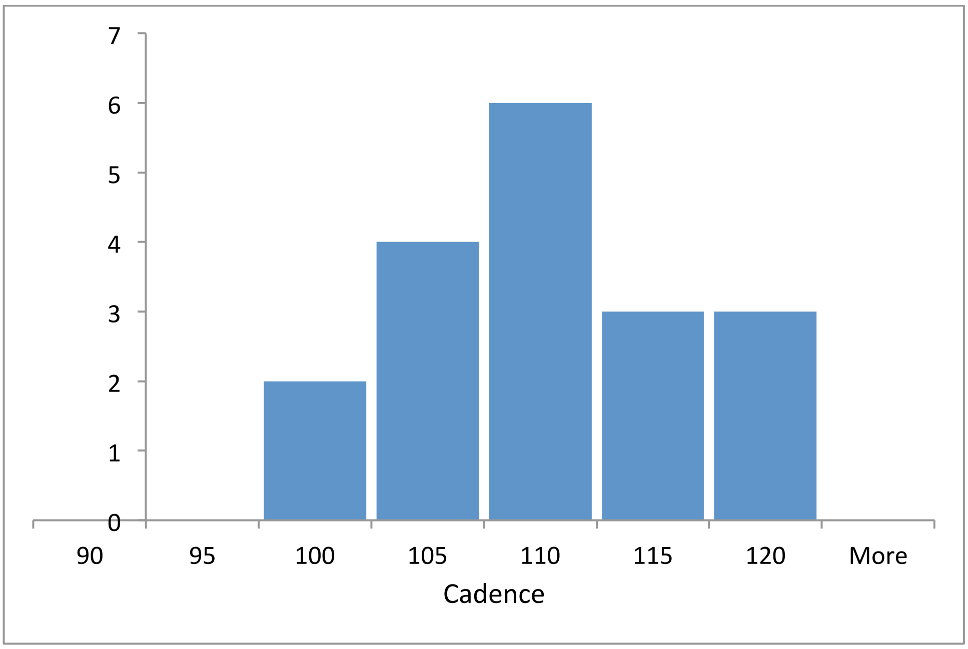
Histogram for Velocity



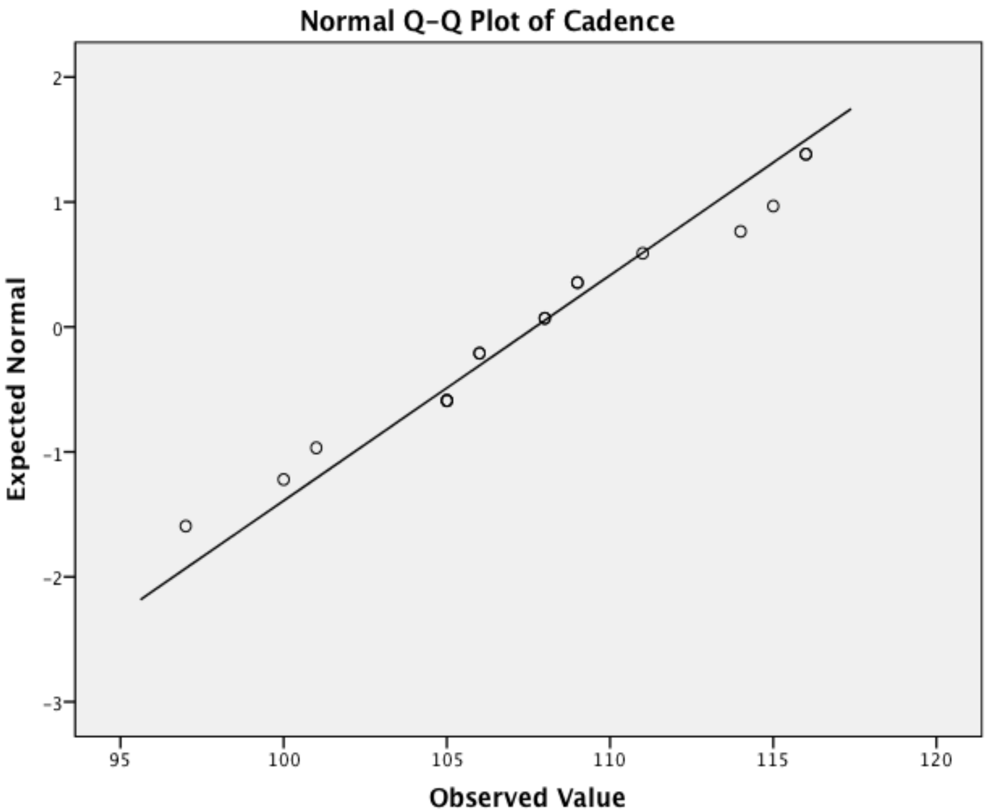
q-q plot for velocity



Histogram for Cadence



q-q plot for cadence



Angular, Kinetic and Kinematic data

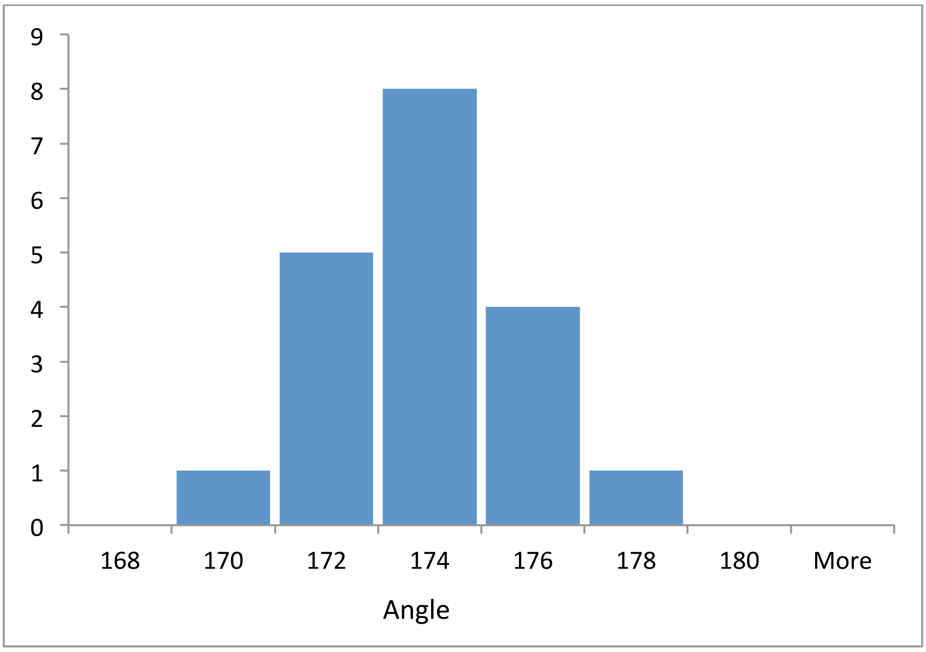
Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	Df	Sig.
Angle	.163	18	.200*	.970	18	.802
FE	.134	18	.200*	.951	18	.447
Coronal	.138	18	.200*	.954	18	.494
FEM	.150	18	.200*	.968	18	.758
AddMom	.131	18	.200*	.966	18	.722

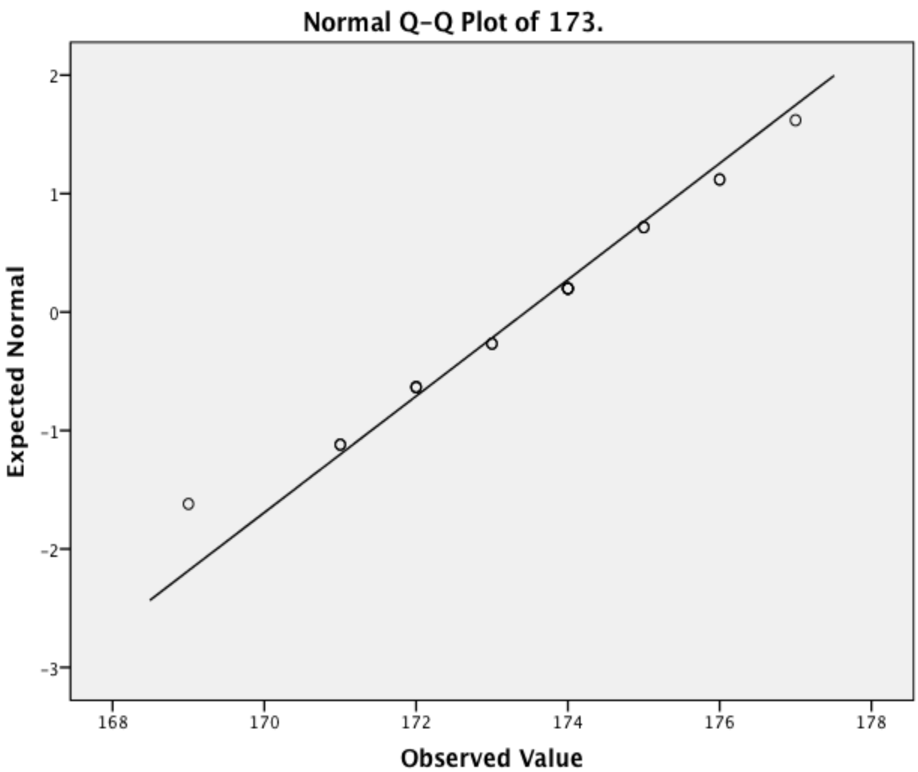
*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

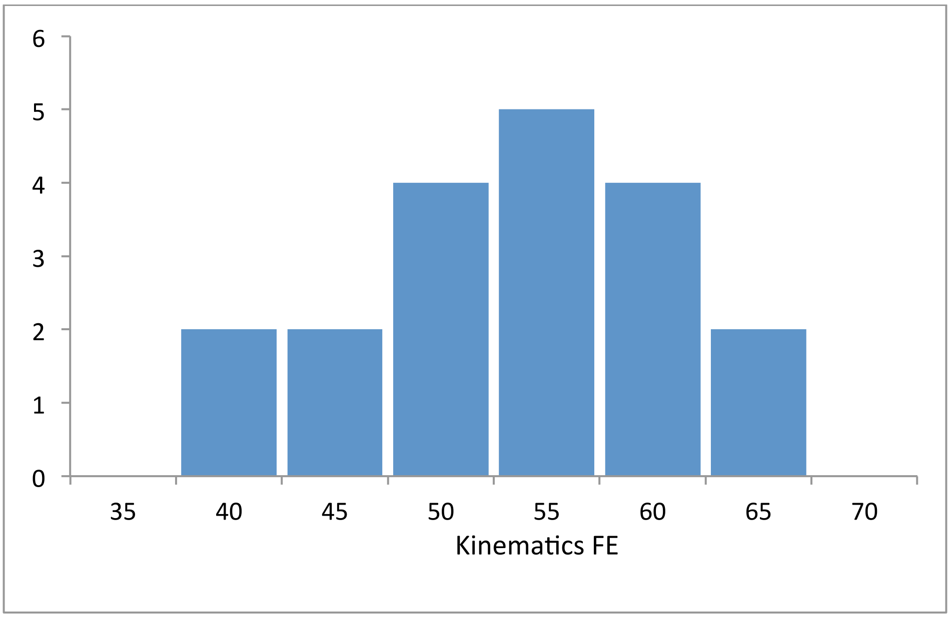
Histogram for HKA Angle



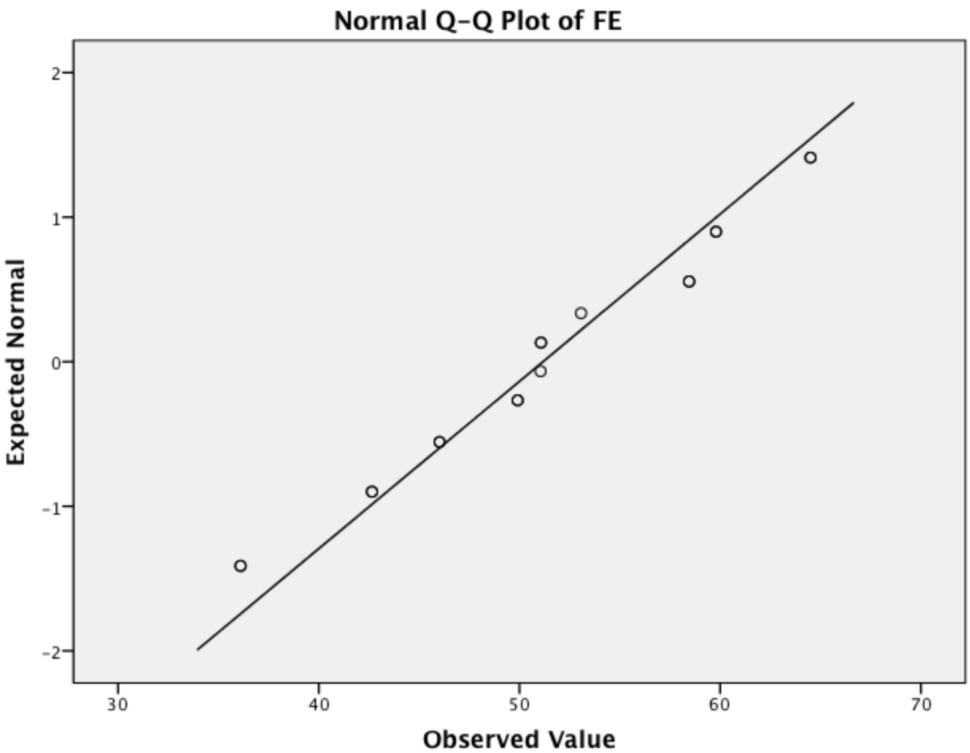
q- q plot for HKA angle



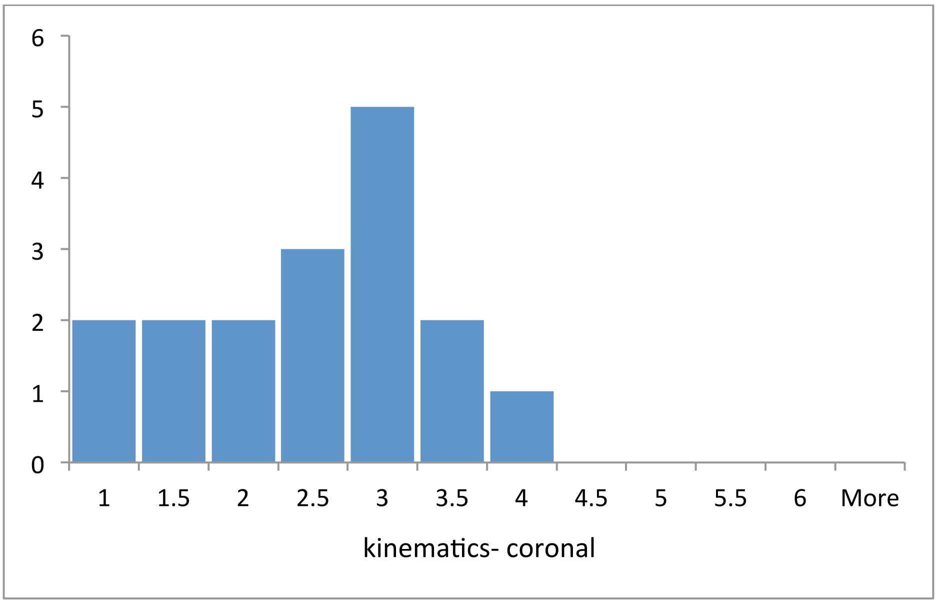
Histogram for Kinetics – Flexion Extension



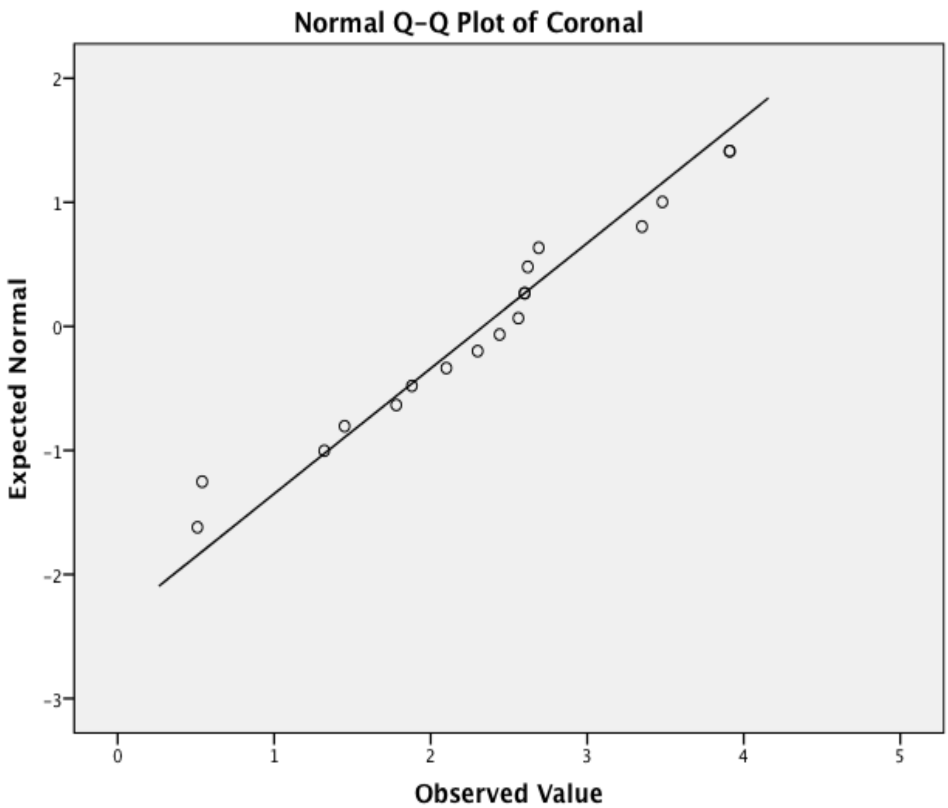
q-q plot for Kinematics FE



Histogram for Kinematics – Coronal

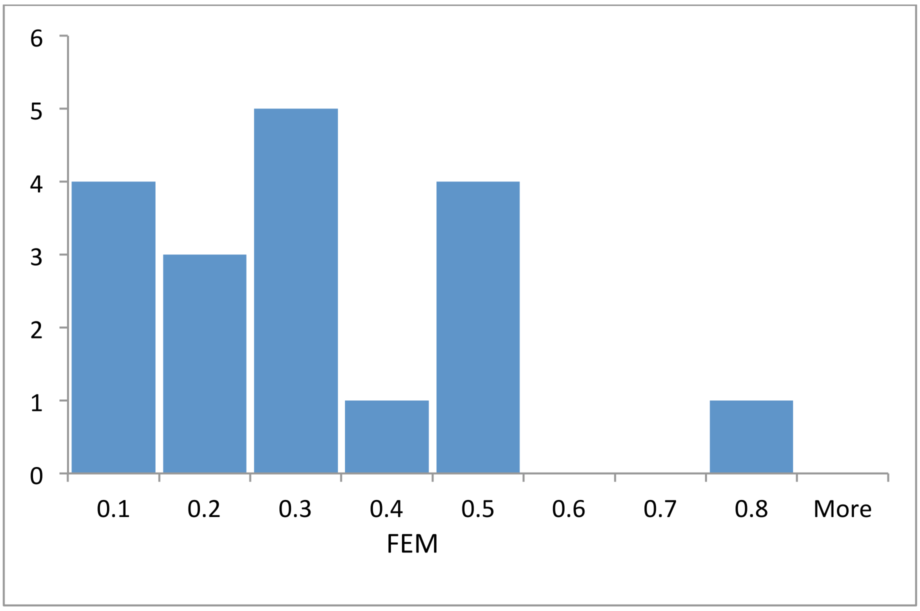


q-q plot for kinematics- coronal

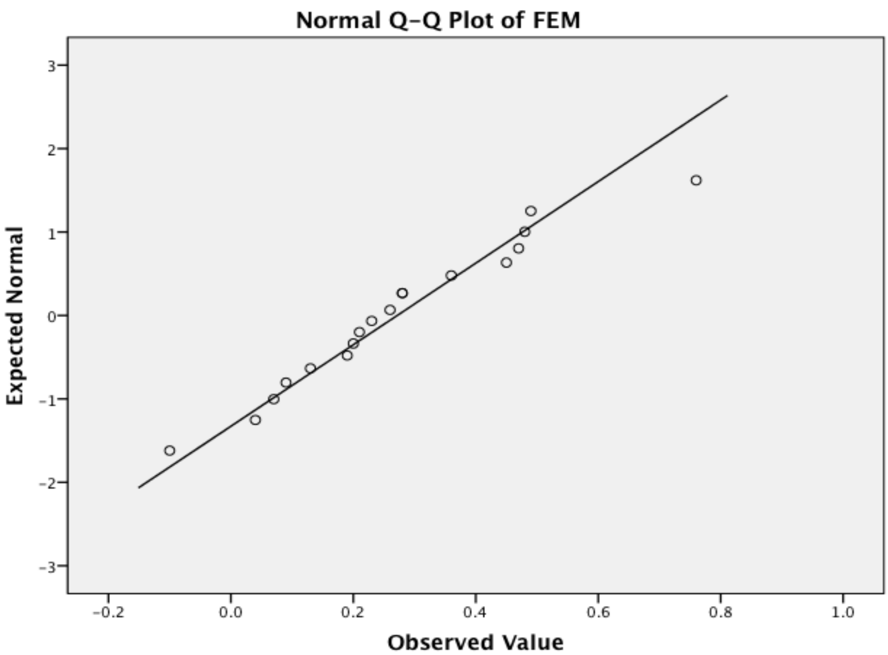


Kinetic data

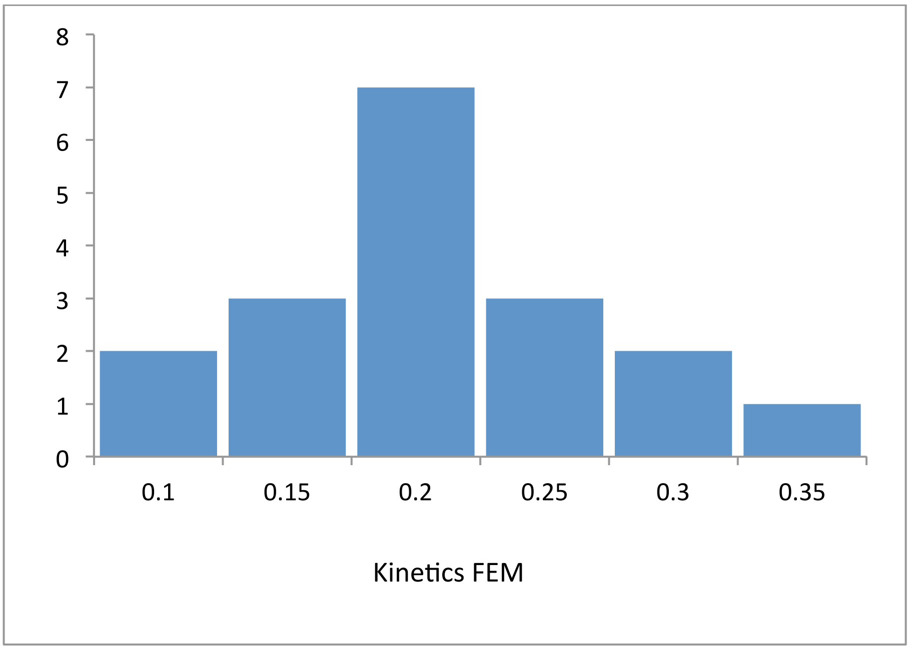
Histogram for Kinetics- FEM



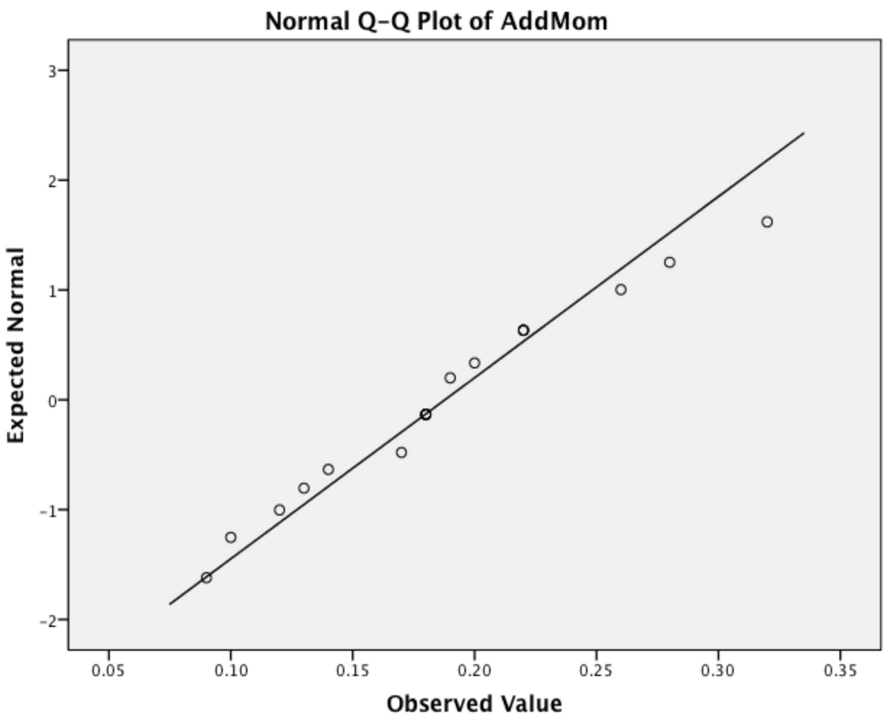
q-q plot for Kinetics FEM



Histogram for Kinetics- Adduction Moment



q-q plot for kinetics - Adduction moment



Box Whisker plot for Kinetics – Adduction moment