Influence of consciousness, muscle action and activity on medial condyle translation after Oxford unicompartmental knee replacement

EC Pegg[1*], J Baré[2], HS Gill[3], HG Pandit[1], JJ O'Connor[4], DW Murray[1], AJ Price[1].

[1] Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences, University of Oxford, Oxford, UK

[2] Melbourne Orthopaedic Group, 33 The Avenue, Windsor, Victoria 3181, Australia

[3] Department of Mechanical Engineering, University of Bath, Bath, UK

[4] Department of Engineering Science, University of Oxford, Oxford, UK

*Corresponding Author:

Dr Elise Pegg

Botnar Research Centre

Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences,

University of Oxford

OX3 7LD

Tel: +44 (0) 1865 227663

Email: elise.pegg@ndorms.ox.ac.uk

Abstract

Background

Quantification of the *in vivo* position of the medial condyle throughout flexion is important for knee replacement design, and understanding knee pathology. The influence of consciousness, muscle action, and activity type on condyle translation was examined in patients who had undergone medial unicompartmental knee replacement (UKR) using lateral video fluoroscopy.

Methods

The position of the centre of the femoral component relative to the tibial component was measured for 9 patients under different conditions. The following activities were assessed; passive flexion and extension when anaesthetised, passive flexion and extension when conscious, active flexion, extension and step-up.

Results

The position of the centre of the femoral component relative to the tibial component was highly patient dependent. The greatest average translation range (14.9 mm) was observed in anaesthetised patients, and the condyle was significantly more anterior near to extension. Furthermore, when conscious but being moved passively, the femoral condyle translated a greater range (8.9 mm) than when moving actively (5.2 mm). When ascending stairs, the femoral condyle was more posterior at 20-30 degrees of flexion than during flexion/extension.

Conclusions

The similarity between these results and published data suggest that knee kinematics following mobile-bearing UKR is relatively normal. The results show that in the normal knee and after UKR, knee kinematics is variable and is influenced by the patient, consciousness, muscle action, and activity type.

Clinical relevance

It is therefore essential that all these factors are considered during knee replacement design, if the aim is to achieve more normal knee kinematics.

Keywords

Knee; Unicompartmental; Kinematics; Fluoroscopy

1 Introduction

Achieving normal kinematic knee function remains a central goal for knee replacement in an effort to maximise patient functional outcome. Debate remains on some aspects of how the normal knee functions, but there is agreement on the central kinematic aspects. The antero-posterior translation of the point of closest contact between the tibia and femur in each compartment (hereafter referred to as the effective articular contact point) is one way of describing relative tibiofemoral movement. There is a general consensus that the effective articular contact point in the medial compartment translates less than the lateral side during flexion and extension, and that this difference reflects axial rotation of the knee [1]. In addition, there is evidence to suggest that the degree of translation varies depending on muscle action (active or passive movement), with some suggesting that the medial articular contact point is nearly static during weight-bearing exercises [1-3].

Oxford unicompartmental knee replacement (UKR) replaces the femoral articular surface of the condyle with a spherical metal component, the tibial articular surface with a flat metal tray, and an interposing conforming mobile polyethylene bearing enables low friction articulation between the two metal components. Unlike the ball and socket joint of the hip, the geometry of the articular surfaces of the human knee joint provides relatively little constraint; although the menisci provide some control, knee stability is heavily reliant on ligaments and muscle action [4]. Hence the operation is indicated only if all four cruciate and collateral ligaments are preserved and functioning. A number of *in-vitro* and *in-vivo* studies have shown that patients after UKR have almost normal knee kinematics [5-7]. However, dynamic *in-vivo* changes in the effective articular contact point position in the loaded and unloaded state has not been studied following UKR. If the articular contact point of the medial condyle translates in a similar manner to that reported for the native knee, it would offer further evidence that the knee after Oxford UKR can reach near normal kinematic function, and would also have implications for knee replacement design in general.

The purpose of this study was to examine the influence of consciousness, muscle action and activity type on the condyle position of the medial compartment of the knee through fluoroscopic measurement of position of the centre of the femoral component on the tibial component after medial UKR surgery, and to compare this with published data on normal knee movement.

2 Patients and Methods

This study examined four main questions regarding the anterior-posterior position of the medial condyle after UKR measured by video fluoroscopy: (1) whether the direction of motion affects the position (i.e. flexion or extension), (2) whether patient consciousness was influential, (3) whether the position varies if the motion is active or passive, and (4) whether different exercises result in different anterior-posterior condyle positioning for equivalent flexion angles.

2.1 Patient Selection

This study was approved by the Central Oxford Research Ethics Committee (ethical approval number 99.144). Patients undergoing medial UKR surgery were invited to participate in the study and the final cohort consisted of 9 patients. The anterior-posterior positioning of the femur relative to the tibia was assessed under seven different conditions; (1) anaesthetised passive knee flexion, (2) anaesthetised passive extension, (3) conscious passive flexion, (4) conscious passive extension, (5) conscious active flexion, (6) conscious active extension and (7) conscious active step-up.

Although all patients were examined for conditions (1) and (2), one of the patients did not return for the follow-up visit. Furthermore, some of the videos were of insufficient quality and so could not be analysed; however, all missing data was accounted for in the statistical analysis.

2.2 Surgical technique

All patients underwent Oxford Phase III UKR in accordance with the standard surgical technique. The ACL was assessed both pre-operatively and intra-operatively, and all patients had a functionally intact ligament. Most patients were operated upon under regional and general anaesthetic, and the surgery was performed by one of the authors (DWM) or under his supervision.

The Oxford UKR surgical technique is designed to restore the anatomic joint level. The tibia is implanted first, and then the femur is implanted to ensure restoration of the joint line. In antero-medial osteoarthritis the posterior femoral cartilage is preserved. The femoral component was implanted so its surface was where the surface of the normal cartilage was, thus retaining the joint line. This was done by removing an appropriate thickness of bone from the posterior femur. Bone was then removed from the distal femur until the ligaments were balanced. Also of note, is that the surgical technique of the Oxford UKR does not attempt to correct any varus/valgus deformity and does not involve release of any ligaments (in particular the MCL).

2.3 Intra-operative anaesthetised passive flexion/extension

After UKR surgery and closure was complete and while the patient was still anaesthetised, a video fluoroscopy (Siemens Siromobile, Siemens Medical, UK) was taken of their operated knee during flexion and extension movements in the sagittal plane. The patient’s leg was placed in a thigh support with the hip flexed to 30 degrees, and the leg was positioned to ensure the support did not impinge on the popliteal fossa; the thigh was also held in place by the examiner during the assessment to minimise error. The lower limb was then moved by the examiner through the full range of flexion and extension while ensuring neutral rotation. A lateral video fluoroscopy was then taken throughout with a frame rate of 15 frames per second.

2.4 Post-operative conscious passive flexion/extension

All post-operative measurements were taken during a follow-up assessment which was approximately 6 months after surgery. The procedure used for the conscious-passive-flexion/extension assessment was similar to that used for the anaesthetised-passive-flexion/extension. The only differences were: the patient was sitting in a chair instead of lying on a table with the thigh supported, and the patient was not anaesthetised. For the passive movement, patients were asked not the resist the movement, and if there was notable resistance the patient was asked to relax and the procedure was repeated. Patients were assessed for their post-operative movements at a minimum of six months post-operatively.

2.5 Post-operative conscious active flexion/extension

The conscious movements were measured during the same follow-up assessment when the passive flexion/extension was examined, approximately 6 months post-operatively. For the active movement, each patient was asked to sit in a chair with the foot unsupported in full flexion (range: 90 to 130 degrees), they were then asked to fully extend their leg while keeping the thigh as still as possible, then to return the leg to the starting position. The patients were also told to keep their foot pointed directly forward throughout the movement. As before, a lateral video fluoroscopy of the knee was taken throughout the activity in the sagittal plane.

2.6 Post-operative conscious active step-up

The step-up activity was assessed during the same follow-up assessment when the passive and active flexion/extension measurements were made. Each patient was asked to stand with one foot positioned on a step, of height 25 cm, so their knee was at approximately 90 degrees of flexion (exact angle was dependent on patient leg length), and with their other leg on the floor. Patients were then asked to step up onto the step but to keep their contralateral leg positioned behind them during the movement so it was outside the field of the fluoroscope. A handrail was provided for patients to stabilise themselves if they needed.

2.7 Video fluoroscopy analysis

Each fluoroscopy video was assessed and frames were selected when the knee was positioned at increments of 10 degrees of flexion. Measurements of knee flexion angle and bearing position were then made on each of these video frames using an imaging software package (Corel Draw v10.0, Corel Corporation Ltd. Ottawa, Canada).

The femoral component was used to find the image magnification; a circle was fitted digitally to the outline of the femoral component with minimum root-square error, and the magnification found from the known implanted femoral component radius. The knee flexion angle was found from the angle between the femoral axis [8] and the tibial axis [9]. The anterior-posterior position of the femoral component (and therefore also the bearing, due to the conforming spherical design of the mobile UKR) relative to the tibia, parallel to the surface of the tibial tray, was calculated. The distance was measured between (1) the intersection point between a line through the centre of surface of the femoral component perpendicular to the surface of the tibial tray, and (2) the most posterior point on the tray keel, where the keel met the underside of the tray (Figure 1).

All condyle position (CP) results were examined relative to the median recorded condyle position for that particular patient (Equation 1) over all the tests performed for each participant in the study (results denoted CP Normalised).

Equation 1. $CP\ Normalised\ = CP\ Result - Median\ CP\ for\ Patient$

2.8 Statistical analysis

The reliability of the fluoroscopy measurement was assessed for both intra- and inter-repeatability. Fluoroscopy videos from 5 patients were assessed for frames at 0 to 100 degrees of flexion at 10 degree intervals. One observer measured the set of images 4 times, and then four observers measured the set of images one time each. The intra-class correlation coefficient (ICC) was calculated using a two-way mixed model [10].

Welch's two-sample unpaired t-tests [11] were performed at each flexion angle to assess whether there were significant differences between: the direction of movement (flexion/extension), patient consciousness (conscious/anaesthetised), and muscle activity (passive/active). When examining patient consciousness and muscle activity, flexing and extending data were grouped together for the test.

A one-way analysis of variance (ANOVA) with a Tukey post-test was used to examine differences between the conscious active flexion, conscious active extension and conscious active step-up exercises.

For each patient at each test condition the overall translation range was calculated from full extension up to 120 degrees of flexion. The effect of the measurement condition (i.e. unconscious, passive or active) on the overall translation range was assessed using a one-way analysis of variance (ANOVA) with a Tukey post-test. All statistical analyses were performed using R software (www.r-project.org).

3 Results

The ICC for the video-based measurement of bearing position had a 95% confidence interval range between 0.978 and 0.992 for the inter-observer reliability, and between 0.92 and 0.969 for the intra-observer reliability.

The position of the femoral condyle within a UKR knee was highly patient dependent; condyle position commonly varied by 10 mm between patients, and at times was as much as 15 mm (Figure 2).

No statistical difference was found between the flexion and extension movements at any flexion angle for the anaesthetised-passive condition, the conscious-passive condition or the conscious-active condition (Table 1, Figure 3). It was therefore deemed valid to merge the flexion and extension data together for later analyses.

From full extension to 30 degrees of flexion, the medial condyle was significantly (up to 4 mm) more anterior when the patients were anaesthetised compared with when they were conscious (Table 1, Figure 4). The overall translation distance was greatest for the anaesthetised patients (Table 2), where the condyle translated a total distance of 14.9 mm on average (flexion:15.6 mm, extension:14.3 mm); the condyle in the conscious patients translated 8.9 mm on average (flexion:9.5 mm, extension:8.4 mm) .

From 10 to 20 degrees of flexion, significant differences were also found between the conscious-active and conscious-passive conditions during flexion and extension (Table 1, Figure 5). For the passive condition, the bearing was 2 mm further anterior compared with the active condition. However, at 110 degrees of flexion this trend was reversed, and the bearing position for the active condition was statistically more anterior than that for the passive condition. As mentioned before, the condyle during passive motion translated 8.9

mm on average from -10 to 120 degrees of flexion; whereas during active motion the condyle translated 5.2 mm on average (flexion:4.4 mm, extension:5.9 mm) (Table 2).

Significant differences were found in the condyle position at certain flexion angles depending on the activity type (Figure 6). The condyle during the step-up activity was significantly more posterior on average between 30 and 40 degrees of flexion compared with active flexion/extension against gravity. The average position of the medial condyle remained posterior throughout the whole activity during step-up, and had an overall translation range of 2.0 mm, whereas the active flexion and extension activities had a translation range of 4.44 mm and 5.90 mm, respectively (Table 2). Nevertheless, medial condyle translation did occur during the step-up activity, and in one patient a relative translation of 3.7 mm was observed between 90 degrees of flexion and full extension (Figure 7).

In terms of the overall range of translation, patients during anaesthetised-passive flexion and extension had significantly greater translation (p-values from 0.002 to 0.043) compared to the conscious-passive and conscious-active exercises (Table 3).

4 Discussion

Clinically, it is important to understand the movement of the knee for two main reasons; to understand knee loading and its influence on developing pathology in the knee (injury or osteoarthritis), and secondly to optimise knee replacement design. The results of this study clearly demonstrate that, after mobile bearing UKR, the medial femoral condyle does translate continuously during flexion; and that consciousness, activity, and exercise type, all influence the range of movement and the anterior-posterior position. This contradicts work by Freeman *et al.*, who have published studies which indicate the majority of tibio-femoral movement occurs in the lateral compartment, and that the medial femoral condyle rocks discontinuously from anterior to posterior between 0 and 30 degrees of flexion, and has little translational movement at higher flexion angles, a so-called medial pivot [1, 12-15]; our results indicate this may be an oversimplification of knee movement. However, our results do show that under certain conditions the medial femoral condyle can be almost static, with movements varying only by ±2 mm from -10 to 120 degrees of flexion. It is therefore important that these results be examined further and the implication for normal knee movement discussed.

The first main observation from this study was that the absolute position of the femoral condyle relative to the tibia was patient dependent (Figure 2). This dependency may relate in part to surgical technique. However, the operation restores anatomy to within 1 or 2 mm, so the much greater variability observed between patients suggests that patient specific factors such as knee anatomy, gait, or muscle condition are much more influential.

At full extension the condyle position was approximately 0 mm for all conscious conditions, however when under anaesthesia the condyle movement was over 6 mm anterior on average. In addition, the condyle was significantly more anterior from -10 to 20 degrees of flexion when the patient was under anaesthesia compared with passive movements when the patient was conscious.

During knee replacement nerve blocks or epidurals are often used and these will relax the muscles beyond their resting state [16]; it is likely that this would increase the laxity of the joint. All patients were able to flex the knee to at least 100 degrees of flexion, and beyond in most cases, so it is unlikely that scar tissue influenced the results. Another possible explanation is that due to the increased hip flexion when the patient was sat in a chair compared with the operating table, the hamstring tendons would have been tighter. The increased tension in the hamstrings in extension would have caused anterior tibial translation due to the line of the action. This in turn would have caused the bearing to be more posterior and could explain the large difference in the anaesthetised and passive results.

At extension, the condyle of the passively moved knee (with the patient conscious) was significantly more anterior than the actively moved knee, and at high flexion the passive knee was more posterior; resulting in a greater overall translation range in the passively moved knee. The results of this study therefore indicate that the muscles have the greatest effect on medial condyle position at the extremes of knee position (10-20 degrees of flexion, and 110 degrees of flexion) when performing a sitting flexion-extension exercise. This finding correlates with previously published work on healthy knees, where the range of motion of the medial condyle during passive motion was shown to be greater than during active motion [12, 13].

The shape of the curves for the passively moved knee condyle translation with flexion compared with the actively moved knee (Figure 5) correlate well with the results of a mathematical model developed by O'Connor *et al.* [17] to represent knee motion. The model calculated the position of the femur for each flexion angle by accounting for geometric constraints, ligamentous constraints and muscle forces; however, the model was purely two-dimensional so could not account for axial rotation, ab/adduction or out of plane translations. This limitation may explain the slight differences in magnitude observed. Zavatsky and O'Connor [18] and Huss, Holstein and O'Connor [19] used a similar model of the intact knee under isometric quadriceps contractions to show that near extension, force in the anteriorly directed patellar tendon strains the ACL whereas, in flexion, force in the posteriorly directed tendon strains the PCL. The relative tibio-femoral translations allowed by these strains could explain the differences between passive and active movements observed in the present experiments.

Statistically this study found differences between the step-up exercise and the extension exercise between 30 and 40 degrees of flexion. Studies have shown that when climbing stairs the normal knee experiences a large external moment at 50 degrees, which is not observed during normal gait [20]; this unusually high moment may influence the medial condyle position. However, apart from this difference, all the active exercises performed were similar in that they all had a relatively small translation range medially (Table 3); the step-up activity had a particularly small average translation range (2.03 mm).

This study has a number of limitations: it may not be valid to extrapolate the movement of the medial condyle after Oxford UKR to the behaviour of healthy knees. However, many of the trends observed in this work match well with studies published in the literature for normal knees; Nakagawa *et al.* showed that the medial condyle in patients moving passively translates more than those moving actively [21]. Furthermore, other parameters such as the patellar tendon angle have been shown in the past to be the same for knees after Oxford UKR and healthy knees [5]. It is worth highlighting that the technique used to assess the translation of the medial condyle in this work is limited only to patients who have undergone Oxford UKR surgery in order to make the measurements. This is because it relies on landmarks which are on the implanted components, and assumes the femur is spherical (which it is for the implanted component, but not for the anatomical femur). Unfortunately, this means that it was not possible to compare the results against a true control, such as the contralateral knee or patients after arthroscopy. The cohort size was small; it was sufficient to observe significant differences and highlight trends, but greater numbers would be necessary to form firm quantitative conclusions.

5 Conclusions

We conclude that the medial condyle can, and does, translate with flexion, but the degree to which it translates depends upon patient factors, consciousness, muscle action and exercise type. Thus, this work highlights the limitations of cadaveric studies, and the importance of studying weight-bearing activities to fully understand knee kinematics.

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Conflict of Interest

One or more of the authors have received or will receive benefits for personal or professional use from a commercial party related directly or indirectly to the subject of this article. In addition, benefits have been or will be directed to a research fund, foundation, educational institution, or other non- profit organisation with which one or more of the authors are associated.

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Tables

Flexion Angle	H1: Difference between flexion and extension			H2: Difference between anaesthet-ised and conscious	H3: Difference between active and passive	H4: Difference between the three activities		
	Anaes-thetised -Passive	Conscio us-Passive	Conscio us-Active			Ext-Flexion	Step up-Flexion	Step up-Ext
-10	0.15	0.47	0.44	0.01	0.50	0.53	0.82	0.84
0	0.95	0.65	0.53	0.00	0.10	0.81	0.91	0.55
10	0.74	0.69	0.47	0.00	0.02	0.75	0.99	070
20	0.96	0.77	0.47	0.01	0.04	0.74	0.68	0.30
30	0.58	0.49	0.40	0.13	0.27	0.68	0.17	0.04
40	0.94	0.52	0.41	0.51	0.73	0.76	0.08	0.03
50	0.69	0.56	0.83	0.90	0.75	0.98	0.11	0.10
60	0.97	0.84	0.47	0.42	0.85	0.76	0.50	0.21
70	0.88	0.85	0.57	0.44	0.65	0.89	0.81	0.56
80	0.48	0.21	0.69	0.68	0.18	0.91	0.93	0.74
90	0.58	0.27	0.85	0.50	0.26	0.98	0.96	0.90
100	0.93	0.30	0.51	0.38	0.27	0.74	0.76	0.44
110	0.45	-	0.57	0.15	0.05	0.82	0.97	0.98
120	0.18	-	0.48	0.24	0.10	0.46	-	-

Table 1. Differences found (p-value) for each of the different hypotheses (H) tested at each flexion angle. Significant values are highlighted in grey.

Test Condition	**Translation Range (mm)**	**Max. Anterior Translation (mm)**	**Max. Posterior Translation (mm)**
Anaesthetised Passive Flexion	15.62	8.70	6.92
Anaesthetised Passive Extension	14.27	6.04	8.24
Conscious Passive Flexion	9.50	3.04	6.46
Conscious Passive Extension	8.35	2.49	5.86
Conscious Active Flexion	4.44	1.39	3.05
Conscious Active Extension	5.90	1.98	3.93
Conscious Step-up	2.03	-0.54	2.57

Table 2. Summary of the overall translation of the medial condyle under the different conditions examined.

		Anaesthetised Passive		**Conscious Passive**		**Conscious Active**		
		Flex	**Ext**	**Flex**	**Ext**	**Flex**	**Ext**	**Step-up**
Anaesthetised Passive	**Flex**		1.00	0.33	0.41	0.01	0.04	<0.01
	Ext			0.22	0.28	0.01	0.02	<0.01
Conscious Passive	**Flex**				1.00	0.98	0.99	0.93

	Ext					0.96	0.99	0.88
Conscious Active	**Flex**						1.00	1.00
	Ext							0.99
	Step-up							

Table 3. Tukey analysis of the one-way analysis of variance test comparing overall condyle translation distance for all datasets. Statistical significance shown for each analysis pair.

Figure Captions

Figure 1. Schematic illustration of how the condyle position (CP) was measured from a lateral radiograph. The area highlighted in red represents a best-fit circle to the femoral component.

Figure 2. Illustration of the patient specific variation observed in condyle position before normalisation and after normalisation; only the results for anaesthetised passive flexion are shown.

Figure 3. Normalised condyle position variation with flexion angle comparing flexion and extension movement directions when the patient was (a) anaesthetised, moving passively (b) conscious, moving passively and (c) conscious, moving actively. The shaded regions represent the inter-quartile range.

Figure 4. Normalised condyle position variation with flexion angle comparing movement when the patient was conscious or anaesthetised; all movements were passive and flexion/extension data were combined. The shaded regions represent the inter-quartile range.

Figure 5. Normalised condyle position variation with flexion angle comparing active to passive movement; all movements were with the patient conscious and flexion/extension data were combined. The shaded regions represent the inter-quartile range.

Figure 6. Normalised condyle position variation with flexion angle, comparing three different activities: flexion, extension and step-up. All movements were with the patient conscious and actively moving. The shaded regions represent the inter-quartile range.

Figure 7. Example frames of a fluoroscopy video of a patient during the step-up activity, when at (a) 90 degrees of flexion, and (b) full extension. The relative translation of the femur measured was 3.7 mm.