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

3 EC Pegg^{1*}, J Baré², HS Gill³, HG Pandit¹, JJ O'Connor⁴, DW Murray¹, AJ Price¹.

4 ¹ Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences,
5 University of Oxford, Oxford, UK

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

7 ³ Department of Mechanical Engineering, University of Bath, Bath, UK

8 ⁴ Department of Engineering Science, University of Oxford, Oxford, UK

9

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11 *Corresponding Author:

12 Dr Elise Pegg

13 Botnar Research Centre

14 Nuffield Department of Orthopaedics, Rheumatology and Musculoskeletal Sciences,

15 University of Oxford

16 OX3 7LD

17 Tel: +44 (0) 1865 227663

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

19 **Abstract**

20 *Background*

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

26 *Methods*

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

31 *Results*

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

39 *Conclusions*

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

44 *Clinical relevance*

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

47 **Keywords**

48 Knee; Unicompartmental; Kinematics; Fluoroscopy

49 1 Introduction

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

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

73 offer further evidence that the knee after Oxford UKR can reach near normal kinematic
74 function, and would also have implications for knee replacement design in general.

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

80 **2 Patients and Methods**

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

87 *2.1 Patient Selection*

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

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

99 2.2 *Surgical technique*

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

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

114 2.3 *Intra-operative anaesthetised passive flexion/extension*

115 After UKR surgery and closure was complete and while the patient was still anaesthetised, a
116 video fluoroscopy (Siemens Siromobile, Siemens Medical, UK) was taken of their operated
117 knee during flexion and extension movements in the sagittal plane. The patient's leg was
118 placed in a thigh support with the hip flexed to 30 degrees, and the leg was positioned to

119 ensure the support did not impinge on the popliteal fossa; the thigh was also held in place by
120 the examiner during the assessment to minimise error. The lower limb was then moved by
121 the examiner through the full range of flexion and extension while ensuring neutral rotation.
122 A lateral video fluoroscopy was then taken throughout with a frame rate of 15 frames per
123 second.

124 *2.4 Post-operative conscious passive flexion/extension*

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

133 *2.5 Post-operative conscious active flexion/extension*

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

142 2.6 *Post-operative conscious active step-up*

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

150 2.7 *Video fluoroscopy analysis*

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

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

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

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

169 2.8 Statistical analysis

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

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

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

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

188 **3 Results**

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

192 The position of the femoral condyle within a UKR knee was highly patient dependent;
193 condyle position commonly varied by 10 mm between patients, and at times was as much as
194 15 mm (Figure 2).

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

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

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

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

213 Significant differences were found in the condyle position at certain flexion angles depending
214 on the activity type (Figure 6). The condyle during the step-up activity was significantly
215 more posterior on average between 30 and 40 degrees of flexion compared with active
216 flexion/extension against gravity. The average position of the medial condyle remained
217 posterior throughout the whole activity during step-up, and had an overall translation range of
218 2.0 mm, whereas the active flexion and extension activities had a translation range of 4.44
219 mm and 5.90 mm, respectively (Table 2). Nevertheless, medial condyle translation did occur
220 during the step-up activity, and in one patient a relative translation of 3.7 mm was observed
221 between 90 degrees of flexion and full extension (Figure 7).

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

225 **4 Discussion**

226 Clinically, it is important to understand the movement of the knee for two main reasons; to
227 understand knee loading and its influence on developing pathology in the knee (injury or
228 osteoarthritis), and secondly to optimise knee replacement design. The results of this study
229 clearly demonstrate that, after mobile bearing UKR, the medial femoral condyle does
230 translate continuously during flexion; and that consciousness, activity, and exercise type, all
231 influence the range of movement and the anterior-posterior position. This contradicts work
232 by Freeman *et al.*, who have published studies which indicate the majority of tibio-femoral
233 movement occurs in the lateral compartment, and that the medial femoral condyle rocks
234 discontinuously from anterior to posterior between 0 and 30 degrees of flexion, and has little

235 translational movement at higher flexion angles, a so-called medial pivot [1, 12-15]; our
236 results indicate this may be an oversimplification of knee movement. However, our results
237 do show that under certain conditions the medial femoral condyle can be almost static, with
238 movements varying only by ± 2 mm from -10 to 120 degrees of flexion. It is therefore
239 important that these results be examined further and the implication for normal knee
240 movement discussed.

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

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

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

258 due to the line of the action. This in turn would have caused the bearing to be more posterior
259 and could explain the large difference in the anaesthetised and passive results.

260 At extension, the condyle of the passively moved knee (with the patient conscious) was
261 significantly more anterior than the actively moved knee, and at high flexion the passive knee
262 was more posterior; resulting in a greater overall translation range in the passively moved
263 knee. The results of this study therefore indicate that the muscles have the greatest effect on
264 medial condyle position at the extremes of knee position (10-20 degrees of flexion, and 110
265 degrees of flexion) when performing a sitting flexion-extension exercise. This finding
266 correlates with previously published work on healthy knees, where the range of motion of the
267 medial condyle during passive motion was shown to be greater than during active motion [12,
268 13].

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

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

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

304 **5 Conclusions**

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

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315 **Conflict of Interest**

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

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Flexion Angle	H1: Difference between flexion and extension			H2: Difference between anaesthetised and conscious	H3: Difference between active and passive	H4: Difference between the three activities		
	Anaesthetised -Passive	Conscious -Passive	Conscious -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	0.70
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	-	-

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

375

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

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

378

		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
	Flex						1.00	1.00
Conscious Active	Ext							0.99
	Step-up							

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

381 **Figure Captions**

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

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

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

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

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

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

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