Sagittal Kinematics of Mobile Unicompartmental Knee Replacement in Anterior Cruciate Ligament Deficient Knees

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Abstract

Background

There is a greater risk of tibial component loosening when mobile unicompartmental knee replacement is performed in anterior cruciate ligament deficient knees. We previously reported on a cohort of anterior cruciate ligament deficient patients (n=46) who had undergone surgery, but no difference was found in implant survivorship at mean 5 year follow-up. The purpose this study was to examine the kinematic behaviour of a subcohort of these patients.

Methods

The kinematic behaviour of anterior cruciate deficient knees (n=16) after mobile unicompartmental knee replacement was compared to matched intact knees (n=16). Sagittal plane knee fluoroscopy was taken while patients performed step-up and forward lunge exercises. The patellar tendon angle, knee flexion angle and implant position was calculated for each video frame.

Findings

The patellar tendon angle was 5° lower in the deficient group, indicating greater anterior tibial translation compared to the intact group between 30 and 40 degrees of flexion. Large variability, particularly from 40-60 degrees of flexion, was observed in the bearing position of the deficient group, which may represent different coping mechanisms. The deficient group took 38% longer to perform the exercises.

Interpretation

Kinematic differences were found between the deficient and intact knees after mobile unicompartmental knee replacement; but these kinematic changes do not seem to affect the medium-term clinical outcome. Whether these altered knee kinematics will have a clinical impact is as yet undetermined, but more long-term outcome data is required before mobile unicompartmental knee replacement can be recommended for an anterior cruciate ligament deficient patient.

Keywords

Unicompartmental knee replacement; Anterior cruciate ligament; Knee kinematics; Function; Patellar Tendon Angle

1. Introduction

Anterior cruciate ligament (ACL) deficiency is considered a contra-indication for mobile Unicompartmental Knee Replacement (UKR). Goodfellow *et al.* in the primary series of the medial Oxford UKR on 103 knees found an association between early implant failure and an absence of the ACL, in particular loosening of the tibial component was commonly observed [21]; a later study on 301 knees also showed reduced survivorship in ACL deficient knees over a 7 year follow-up period [22]. Both Deschamps *et al.* [14] and Böhm *et al.* [8]reported similar findings with fixed bearing unicompartmental prostheses, where patients with an absent ACL represented a large proportion of the failures (41% [8]) involving aseptic loosening and tibial subluxation. As a result of these findings, mobile-bearing UKR in patients with a deficient ACL is rarely performed and consequently there are few published studies on such patients.

However, there is some evidence that a UKR can be successful in an ACL-deficient knee. Engh *et al.* performed a prospective study on 72 patients with ACL-deficiency (but who had reported no knee instability) who underwent fixed-bearing UKR [16]; their results showed no difference in survivorship at a mean follow-up of 6 years. Boissonneault *et al.* analysed an ACL-deficient patient group retrospectively who had undergone mobile UKR. No differences in survivorship, implant slope or patient reported outcome measures were found at a mean follow-up of 5 years [9]. The reason why these findings contradict those reported by Goodfellow *et al.* and Böhm *et al.* is not fully understood. Engh *et al.* and Boissonneault *et al.* both hypothesise that the differences could be due to modified operative technique and/or patient selection.

Studies examining ACL-deficient patients who have not undergone knee replacement have found significantly different knee kinetics and kinematics during stair-climbing [10,31,27,1,41], walking [10,7,33,26,28], and squatting [13] activities. Although there is some controversy in the literature regarding particular differences, the majority of authors agree on the following observations for patients with ACL-deficient knees:

- The affected knees have greater anterior tibial translation from 0-30 degrees of flexion [27,1]
- Patients perform activities with a reduced quadriceps force and a decreased external knee flexion moment [10,7,33,28,4]; some studies suggest this is also time-dependent [26,40]
- Patients have increased activity in the vastus lateralis component of the quadriceps muscle, reducing overall internal rotational forces on the knee [10,26]

- Patients take longer to perform activities [41,31]

The use of fluoroscopy to assess the knee kinematics in the sagittal plane of the knee is an established technique for UKR [34,35]. The majority of knee motion occurs in the sagittal plane, and patellar motion represents information on both the translation of the femur relative to the tibia, and the patellar relative to the femur [29]. In particular, the patellar tendon angle (PTA) has been used to represent knee kinematics.

The PTA is influenced by two main factors; the geometrical shape of the femur on which the patellar articulates (which is therefore dependent on flexion angle), and the anterior-posterior position of the femur on the tibia [43,20]. By comparing the PTA at each flexion angle of different groups, it is possible to quantify differences in anterior-posterior positioning and movement reproducibility. The PTA also has the particular advantage of not being significantly influenced by internal/external rotation of the knee; studies have shown that 20 degrees of rotation only causes a 1° change in the measured PTA [36]. Also of importance to UKR knee kinematics is knowledge of how the medial compartment in particular translates; it is possible to determine this through assessment of the medial femoral implant position relative to the tibial implant (bearing position measurement) [34].

The goal of this study was to examine a subset of the cohort of ACL-deficient (ACLD) knees studied by Boissonneault *et al.* [9] who had undergone mobile medial UKR, and compare their knee kinematics to a matched cohort of ACL-intact (ACLI) knees using sagittal plane video fluoroscopy. The hypothesis examined in this study was that there is a difference in PTA, and bearing position, in ACLD knees compared with ACLI knees throughout flexion.

2. Methods

2.1 Patient Selection

This study was approved by the Oxford Research Ethics Committee B (13/SC/008). The patient group consisted of patients with ACL-deficient knees who had undergone Phase III Oxford UKR (Biomet UK Healthcare Ltd., Swindon, UK) between January 2000 and June 2011. ACL-deficient patients were defined as those with either no ACL, or had an ACL where less than 50% of the fibres were intact and it was functionally inactive (as determined from an intra-operative positive pivot-shift test). Although ACL-deficiency is considered a contra-indication for mobile unicompartmental knee replacement, in unusual cases the procedure has been performed in ACL-deficient knees in our centre, mostly at the request of the patient; detailed information on this particular cohort of patients has been previously published [9].

The control group was found by matching the participating ACL-deficient patients to ACL-intact patients for age, sex, and follow-up time since UKR surgery. All patients included in the study were; willing and able to give informed consent and had undergone a medial Oxford UKR performed by a senior surgeon. Patients were excluded from the study if; they were physically unable to perform either activity, the Oxford UKR had been revised, they had undergone total hip replacement, they were under 18 years of age, or they were part of another conflicting research study.

The resultant cohorts consisted of 16 ACL-deficient and 16 ACL-intact knees; no significant difference was found in terms of age, follow-up time or sex (Table 1). To ensure sufficient participants for the study, a power calculation was performed. The calculated minimum required sample size was 12 for each group, assuming a measurement standard deviation (SD) of 3.3° [34], a clinically significant difference of 4° [32], a power of 0.8, and 5% significance.

2.2. Patient-Reported Outcome Measures (PROMs)

After consent and prior to the fluoroscopy assessment, all participants were asked to complete three questionnaires; the Oxford Knee Score (OKS) [12], the Tegner Activity Score [44], and a Visual Analogue Scale (VAS) Pain score between 0 and 100, where 100 is the worst pain imaginable [42].

2.3. Video Fluoroscopy

Video fluoroscopy of each knee in the sagittal plane was recorded during two activities; step-up and a forward lunge. The step up activity was chosen because; it is a functional activity which is commonly performed, it has been shown to cause large strains within the ACL (~2.8% [18]) and a high flexion moment within the knee [3], it covers a large flexion range, and it requires significant quadriceps force which causes an anterior tibial translation force up to 60 degrees of flexion and internal tibial rotation [10]. The forward lunge activity was chosen because; it is a weight-bearing activity performed at flexion angles above 90° and it has been shown to involve minimal ACL strain [18] and therefore can provide information on indicate indirect adaptations to the deficiency, such as muscular differences.

A strict protocol was followed to instruct the patients how to perform the exercises. The clinician first gave a verbal description of the exercise to the patient, the clinician then demonstrated the exercise, after which the patient was asked to duplicate the activity at a speed comfortable to them and given the opportunity to ask any questions. Subsequently, the fluoroscopy video was captured while the patient performed the exercise.

At the start of the step-up activity the foot of the leg being assessed was positioned on the step and the foot of the contralateral leg was on the floor. The patient was then asked to step up onto the step but to keep their contralateral leg positioned behind them so it was outside the field of the fluoroscope (Figure 1a). The step height was varied to ensure the leg was at 90 degrees of flexion at the start of the activity enabling consistency for different leg lengths. Patients were told they could stabilise themselves using a handrail with the arm contralateral to the knee being examined if they wished; the patients were asked to keep their other arm positioned behind their back. No other instructions were given to the patients; the goal was to ensure the patients moved as naturally as possible.

At the start of the forward lunge activity on the step, the patient was in a similar position to the step-up activity, but the foot of the contralateral leg was farther back (Figure 1b). Patients were asked to lower their trunk so their knee flexed while keeping their assessed knee in the field of the fluoroscopy. As before, patients were told they could stabilise themselves using a handrail if they wished.

After each fluoroscopy, a static radiograph was taken of a reference grid, consisting of two Perspex sheets with radio-opaque markers at known locations, positioned in the same location as the patient knee during the video capture.

2.4. Fluoroscopy Video Analysis

Using MATLAB software (version 7.10, MathWorks Inc. MA, USA) each video was separated into frames and each image was analysed separately. Pin-cushion and barrel distortions were quantified from the position of the calibration grid marker balls in the radiograph (calculation performed with the validated MATLAB "cp2tform" function which uses a weighted least-squares method [23]). The distortion correction was then applied to all frames within the video.

A custom MATLAB user-interface was created to enable the user to select anatomical landmark points in each frame; this data was then used to calculate the knee flexion angle (KFA), PTA and bearing position (BP). The KFA was the angle between the femoral axis [38] (Figure 2, line A) and the tibial axis [15] (Figure 2, line B), the PTA was the angle between the patellar-tendon axis (Figure 2, line C) and the tibial axis (Figure 2, line B). The spherical femoral component was used to calculate the scale by fitting a circle to 10 selected points surrounding the component. It was necessary to measure the BP indirectly due to the radiolucency of the polyethylene; therefore, it was assumed that the centre of curvature of the upper bearing surface would coincide with that of the femoral component surface because the surfaces are conforming. The BP was quantified as the distance from the tibial tray keel midpoint to the projected point of the femoral component centre on the tray keel (Figure 2, distance D). Anterior movement was denoted as positive and posterior movement as negative. The duration of each video in seconds was also recorded as a measure of how long the patient took to perform the exercise.

2.5. Statistics

Differences in patient outcome scores between the two groups were assessed using a paired non-parametric Wilcoxon signed-rank test. An independent samples non-parametric test (Mann-Whitney U test) was performed to examine differences in the PTA and BP for the groups at each flexion angle. The same test was used to assess differences in the time taken to perform the exercise. Cohen's *d* effect sizes were also calculated for each test.

Two repeats of the measurements from 6 knees for each activity were made to calculate the intra-observer reliability [5]. The intra-observer correlation coefficient was found using a two-way mixed model with single measures. All statistical calculations were performed using the statistical software environment R (version 2.15.1, www.r-project .org).

3. Results

No significant difference was found in the OKS, the pre-operative to post-operative change in OKS, the Tegner Activity Score or the VAS Pain score, between the ACLD and the ACLI groups (Table 2). The intraclass correlation coefficient was 0.968 for the PTA measurements, and 0.964 for the BP measurements. Analysis of the videos revealed that the ACLD group took significantly longer than the ACLI group to perform both the step-up (30.7% longer, Table 5) and the forward lunge (45.0% longer, Table 5) activities (Figure 5).

The PTA reduced almost linearly with increasing knee flexion angle. The mean PTA was 5° lower for the ACLD group at 30-40 degrees of flexion and the difference between the groups was significant (Figure 3, Table 3). Significant reductions in the PTA for the ACLD group were also observed at 60 degrees of flexion during the step-up activity, and for the forward lunge activity at 100 and 110 degrees of flexion.

The bearing moved posteriorly on average with extension during the step-up exercise (Figure 4). The BP in the ACLD group had a 95% confidence interval of over 15 mm between 40 and 60 degrees of flexion. This contrasted with the relatively low range of results in the ACLI group, where the confidence interval did not exceed 2 mm. The position of the bearing was shown to be patient dependent (p=0.038); indicating that some patients tended to be anterior/posterior throughout flexion. Throughout the forward lunge exercise the ACLD group bearings were significantly more anterior on average compared to the ACLI group (Table 4). The bearing in both groups moved posteriorly with increasing flexion angle during the forward lunge exercise, which was opposite to the step-up activity.

4. Discussion

The purpose of this study was to examine the hypothesis that the sagittal plane knee kinematics after UKR in an ACL-deficient knee is different to an ACL-intact knee. The results have shown that there are differences in the PTA and the BP in ACLD knees, and it is important to examine the meaning of these findings.

The approximately linear reduction of PTA with flexion angle observed in this study, reaching zero approximately 80 degrees, correlates well with previous studies on knee kinematics in healthy knees after mobile bearing UKR for both intact and reconstructed ligaments [34,35]. Work by Gill and O'Connor found that the linear reduction of PTA with flexion angle was a combination of roll back of the femur (accounts for a third of the change) and the changing shape of femur in articulation with the patella (accounts for two thirds of the change) [20].

At both 30 and 40 degrees of flexion the PTA was significantly reduced in the ACLD group. The PTA gives an indication of the position of the femur on the tibia in the mid-sagittal plane. The 5° relative difference in PTA between the groups indicates the tibia was more anterior relative to the femur in the ACLD group at that particular flexion angle during the step-up exercise [34].

The additional 5° reduction in the PTA at 30-40 degrees of flexion observed in this study for ACLD knees after UKR has not been previously reported. However, ACLD knees in general, which have not undergone mobile UKR, have been shown to have increased tibial translation at 30 degrees of flexion, which would correlate with a reduction in PTA [27,1]. Nearer extension, the forward pull of the patellar tendon (Figure 3) would be resisted by stretch of the ACL in the ACLI group but not in the ACLD group. Fleming *et al.* found that during a step-up exercise, the strain within the ACL is maximal at approximately 20 degrees of flexion [18], supporting the theory that the increased tibial translation is due to the ACL deficiency. Differences diminish close to full extension where the quadriceps and ACL forces would be expected to be smallest [24].

At higher flexion angles the hamstrings are more effective at counteracting anterior tibial translation, therefore differences between the ACL-deficient and ACL-intact groups during the forward lunge activity would not be expected [27,30,39]. However, significant differences were observed between the groups at 60, 100 and 100 degrees of flexion. At these flexion angles the influence of the ACL on anterior-posterior positioning of the knee would be small [18], therefore cannot be directly due to differences in anterior cruciate ligament function.

It has been proposed that patients after ACL injury often develop different compensatory mechanisms to restore stability to the knee. One method is to use the hamstrings for stability; ACLD patients have been shown to have increased hamstring muscle activation [2] and to use their hamstrings more often during an activity [6]. Alternatively ACLD patients can adopt a quadriceps avoidance gait thus reducing the resultant anterior tibial force. The quadriceps can be avoided by either walking with a reduced knee flexion angle during midstance, or leaning forward with the trunk to decrease the strain placed on the quadriceps during midstance [37]. As patients were given no restriction or advice on their trunk position, or flexion angle when performing the activities, it is possible that the differences observed at 60, 100 and 110 degrees of flexion are a result of these different compensatory mechanisms.

During the step-up activity, a large degree of variation was observed in the BP between 40 and 60 degrees of flexion for the ACLD patient group. It is possible that the variation observed was a result of different mechanisms for coping with ACL-deficiency in the ACLD patient group. In the ACLD group the bearing translated 4.5 mm anteriorly on average as the knee flexed from 0-90 degrees of flexion; this could also be considered 4.5 mm posterior tibial translation. During step up, we would expect the quadriceps force to be maximal at 90 degrees of flexion and to diminish as the knee extends. In flexion, posterior translation of the tibia relative to the femur induced by the posteriorly directed patellar tendon (Figure 4) would be resisted by the stretch of the PCL. Thus, there were smaller differences in BP between the ACLD and ACLI groups at higher flexion angles, each with an intact PCL [25].

The ACLD patient group took longer to perform the exercises than the ACLI group in this study, this finding correlates with other studies on ACLD knees [31,41]. Some studies have suggested this is due to the loss of proprioception from the ACL, and that consequently some patients adapt by using more guarded movements to maintain knee stability [41,11].

The present study has some limitations. An important limitation of this study was that only the sagittal plane of the knee was examined, thus knee rotation was not quantified. ACL-deficiency has been shown to have a significant influence on internal rotation [45] and there may have been rotational differences between the groups which were undetected. Furthermore, the measurements of the fluoroscope images were performed by only one person which could have introduced some bias; however, the intra-observer reliability results indicated good repeatability and the values observed correlated well with published data. It is possible that trunk lean had an effect on the results of this study as patients were not instructed to keep their back straight but were asked to move as naturally as possible. Efforts were made to match the patient groups, but patients were not matched for body mass, pre-operative PROMs, or for tibial slope; it is therefore possible that these variables may have influenced the data. Within the ACL-deficient group, the patients had varying degrees of ACL-deficiency (fragmented/absent) but it was not possible to examine the influence of this given the sample size; however, whether the ACL is absent or fragmented, neither can provide tibial constraint.

Whether differences in knee kinematics correlate with differences in clinical outcome is not known at this stage. However, knee instability is often cited as a cause of dissatisfaction after knee replacement [17], and a reduction in PTA has been directly correlated with knee instability [19], so it is probable that PTA is a relevant measure. In the present study none of the patients (in either group) complained of knee instability and none had a positive pivot shift test at pre-operative assessment; thereby suggesting that none of the patients in the study had symptomatic instability. This could explain the lack of differences observed in the clinical outcomes between the groups, even though there were significant differences in the knee kinematics.

5. Conclusions

The main findings from this study can be summarised as follows:

- ACL-deficient patients after UKR have different knee kinematics compared to ACL-intact patients
- Differences were particularly noticeable during step-up ranging from 30 to 60 degrees of flexion and it is possible that muscle imbalance and/or loss of proprioception may be a factor.
- The ACL-deficient group took significantly more time to perform the activities.
- Large variation in bearing position was observed for ACLD patients

- Overall, the kinematics of the ACLD knees were closer to healthy knees than reported data for total knee replacement devices, but were not as similar to healthy knees than ACL-reconstructed UKR knees [34].

It is unknown exactly what impact the different kinematics observed in ACL-deficient patients after UKR will have clinically, but based on these results it would be advised to avoid performing the procedure in ACL-deficient patients until the significance of these results are better understood and longer term outcome data for this cohort is reported.

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References

1. Ahmed AM, McLean C (2002) In vitro measurement of the restraining role of the anterior cruciate ligament during walking and stair ascent. J Biomech Eng 124:768-779

2. Andriacchi TP (1990) Dynamics of pathological motion: Applied to the anterior cruciate deficient knee. J Biomech 23, Supplement 1:99-105

3. Andriacchi TP, Andersson GB, Fermier RW, Stern D, Galante JO (1980) A study of lower-limb mechanics during stair-climbing. J Bone Joint Surg [Am] 62:749-757

4. Andriacchi TP, Birac D (1993) Functional testing in the anterior cruciate ligament-deficient knee. Clin Orthop Relat Res 288:40-47

5. Bartko JJ (1966) The intraclass correlation coefficient as a measureof reliability. Psychol Rep 19:3-11

6. Beard DJ, Soundarapandian RS, O'Connor JJ, Dodd CAF (1996) Gait and electromyographic analysis of anterior cruciate ligament deficient subjects. Gait & Posture 4:83-88

7. Berchuck M, Andriacchi TP, Bach BR, Reider B (1990) Gait adaptations by patients who have a deficient anterior cruciate ligament. J Bone Joint Surg [Am] 72:871-877

8. Böhm I, Landsiedl F (2000) Revision surgery after failed unicompartmental knee arthroplasty: A study of 35 cases. J Arthrop 15:982-989

9. Boissonneault A, Pandit H, Pegg E, Jenkins C, Gill HS, Dodd CA, Gibbons CL et al. (2013) No difference in survivorship after unicompartmental knee arthroplasty with or without an intact anterior cruciate ligament. Knee Surg Sport Tr A 21:2480-2486

10. Ciccotti MG, Kerlan RK, Perry J, Pink M (1994) An electromyographic analysis of the knee during functional activities. II. The anterior cruciate ligament-deficient and -reconstructed profiles. Am J Sports Med 22:651-658

11. Courtney C, Rine RM, Kroll P (2005) Central somatosensory changes and altered muscle synergies in subjects with anterior cruciate ligament deficiency. Gait Posture 22:69-74

12. Dawson J, Fitzpatrick R, Murray D, Carr A (1998) Questionnaire on the perceptions of patients about total knee replacement. J Bone Joint Surg [Br] 80-B:63-69

13. DeFrate LE, Papannagari R, Gill TJ, Moses JM, Pathare NP, Li G (2006) The 6 degrees of freedom kinematics of the knee after anterior cruciate ligament deficiency: an in vivo imaging analysis. Am J Sports Med 34:1240-1246

14. Deschamps G, Lapeyre B (1987) Rupture of the anterior cruciate ligament: a frequently unrecognized cause of failure of unicompartmental knee prostheses. Apropos of a series of 79 Lotus prostheses with a follow-up of more than 5 years. Revue de chirurgia orthopedique et reparatrice de l'appareil moteur 73:544-551

15. Eijden Tv, Kouwenhoven E, Weijs WA (1987) Mecahnics of the patellar articulation. Effects of patellar ligament length studied with a mathematical model. Acta Orthop Scand 58:560-566

16. Engh G, Ammeen D (2014) Unicondylar arthroplasty in knees with deficient anterior cruciate ligaments. Clin Orthop Relat Res 472:73-77

17. Fehring TK, Valadie AL (1994) Knee Instability After Total Knee Arthroplasty. Clin Orthop Relat Res 299:157-162

18. Fleming BC, Beynnon BD, Renstrom PA, Johnson RJ, Nichols CE, Peura GD, Uh BS (1999) The Strain Behavior of the Anterior Cruciate Ligament During Stair Climbing: An In Vivo Study. Arthroscopy 15:185-191

19. Gauffin H, Tropp H (1992) Altered movement and muscular-activation patterns during the one-legged jump in patients with an old anterior cruciate ligament rupture. Am J Sports Med 20:182-192

20. Gill HS, O'Connor JJ (1996) Biarticulating two-dimensional computer model of the human patellofemoral joint. Clin Biomech 11:81-89

21. Goodfellow J, Kershaw C, Benson M, O'Connor JJ (1988) The Oxford Knee for unicompartmental osteoarthritis. The first 103 cases. J Bone Joint Surg [Br] 70B:692-701

22. Goodfellow J, O'Connor J (1992) The Anterior Cruciate Ligament in Knee Arthroplasty: A Risk-Factor With Unconstrained Meniscal Prostheses. Clin Orthop Relat Res 276:245-252

23. Goshtasby A (1988) Image registration by local approximation methods. Image Vis Comput 6:255-261

24. Hirokawa S, Solomonow M, Lu Y, Lou Z-P, D'Ambrosia R (1992) Anterior-posterior and rotational displacement of the tibia elicited by quadriceps contraction. Am J Sports Med 20:299-306

25. Huss RA, Holstein H, O'Connor JJ (2000) A mathematical model of forces in the knee under isometric quadriceps contractions. Clin Biomech 15:112-122

26. Knoll Z, Kiss RM, Kocsis L (2004) Gait adaptation in ACL deficient patients before and after anterior cruciate ligament reconstruction surgery. J Electromyogr Kines 14:287-294

27. Kvist J, Gillquist J (2001) Anterior positioning of tibia during motion after anterior cruciate ligament injury. Med Sci Sports Exerc 33:1063-1072

28. Lewek M, Rudolph K, Axe M, Snyder-Mackler L (2002) The effect of insufficient quadriceps strength on gait after anterior cruciate ligament reconstruction. Clin Biomech 17:56-63

29. Li G, Papannagari R, Nha KW, DeFrate LE, Gill TJ, Rubash HE (2007) The Coupled Motion of the Femur and Patella During In Vivo Weightbearing Knee Flexion. Journal of Biomechanical Engineering 129:937-943. doi:10.1115/1.2803267

30. Li G, Rudy TW, Sakane M, Kanamori K, Ma CB, Woo SL (1999) The importance of quadriceps and hamstring muscle loading on knee kinematics and in-situ forces in the ACL. J Biomech 32:395-400

31. Lin H-C, Hsu H-C, Lu T-W (2011) Bilateral changes in ground reaction forces in patients with unilateral anterior cruciate ligament deficiency during stair locomotion. J Mech 27:437-445

32. Liu W, Maitland ME (2000) The effect of hamstring muscle compensation for anterior laxity in the ACL-deficient knee during gait. Journal of Biomechanics 33:871-879. doi:http://dx.doi.org/10.1016/S0021-9290(00)00047-6

33. Noyes FR, Schipplein OD, Andriacchi TP, Saddemi SR, Weise M (1992) The anterior cruciate ligament-deficient knee with varus alignment. An analysis of gait adaptations and dynamic joint loadings. Am J Sports Med 20:707-716

34. Pandit H, Duren BHv, Gallagher JA, Beard DJ, Dodd CA, Gill HS, Murray DW (2008) Combined anterior cruciate reconstruction and Oxford unicompartmental knee arthroplasty: in vivo kinematics. Knee 15:101-106

35. Pandit H, Ward T, Hollinghurst D, Beard DJ, Gill HS, Thomas NP, Murray DW (2005) Influence of surface geometry and the cam-post mechanism on the kinematics of total knee replacement. J Bone Joint Surg [Br] 87:940-945

36. Pandit HG (2009) Sagittal plane kinematics after knee arthroplasty. University of Oxford, D.Phil Thesis

37. Patel RR, Hurwitz DE, Andriacchi TP, Bush-Joseph CA, Bach BR, Jr. (1996) Mechanisms for the “Quadriceps Avoidance Gait” seen in ACL deficient patients. Gait & Posture 5:147

38. Rees JL, Price AJ, Beard DJ, Robinson BJ, Murray DW (2002) Defining the femoral axis on lateral knee fluoroscopy. Knee 9:65-68

39. Renstrom P, Arms SW, Stanwyck TS, Johnson RJ, Pope MH (1986) Strain within the anterior cruciate ligament during hamstring and quadriceps activity. Am J Sports Med 14:83-87

40. Roberts CS, Rash GS, Honaker JT, Wachowiak MP, Shaw JC (1999) A deficient anterior cruciate ligament does not lead to quadriceps avoidance gait. Gait Posture 10:189-199

41. Rudolph KS, Snyder-Mackler L (2004) Effect of dynamic stability on a step task in ACL deficient individuals. J Electromyogr Kines 14:565-575

42. Scott J, Huskisson EC (1988) Graphic representation of pain. Pain 2:175-184

43. Stagni R, Fantozzi S, Catani F, Leardini A (2010) Can Patellar Tendon Angle reveal sagittal kinematics in total knee arthroplasty. Knee Surg Sport Tr A 18:949-954

44. Tegner Y, Lysholm J (1985) Rating systems in the evaluation of knee ligament injuries. Clin Orthop Relat Res 198:43-49

45. Zantop T, Herbort M, Raschke MJ, Fu FH, Petersen W (2007) The Role of the Anteromedial and Posterolateral Bundles of the Anterior Cruciate Ligament in Anterior Tibial Translation and Internal Rotation. Am J Sports Med 35:223-227

Table and Figure Captions

	ACLD	ACLI	*p*-value	Effect size
Number of Knees	16	16		
Number of Patients	14	13		
Mean Age [years (range)]	67.0 (50-87)	68.3 (49-86)	0.80	0.11
Mean Follow-up Time [years (range)]	6.3 (1.3-12.8)	6.0 (2.6-11.0)	0.82	0.11
Gender	12 male, 2 female	12 male, 1 female	0.32	

Table 1. Age, time to follow-up and sex of the ACLD and ACLI patient cohorts. Differences in the cohorts were found to be not significant.

	ACLD	ACLI	*p*-value	Effect size
Oxford Knee Score (range)	40.7 (20-48)	42.3 (32-48)	0.35	0.25
Change in Oxford Knee Score (range)	15.9 (2-33)	12.9 (2-27)	0.57	0.42
Tegner Activity Score (range)	3.2 (2-5)	2.8 (0-5)	0.15	0.61
VAS Pain Score (range)	16.6 (0-70.3)	10.7 (0-85.9)	0.73	0.23

Table 2. Patient-recorded outcome scores for the ACLD and ACLI groups; differences between groups were not significant.

KFA (degrees)	PTA (degrees)		*p*-value	Effect size
	ACLD	**ACLI**		
Step-up				
0	14.30	16.13	0.074	0.487
10	13.83	14.60	0.291	0.219
20	10.17	11.79	0.101	0.419
30	4.64	9.88	1.061e-6	1.369
40	3.76	8.25	1.669e-3	1.353
50	4.21	5.84	0.094	0.423
60	0.91	3.48	0.007	1.088
70	0.98	1.70	0.864	0.034
80	-0.38	-0.86	0.844	0.140
90	-3.24	-2.87	0.753	0.017
Knee Bend				
90	-3.59	-3.64	0.994	0.114
100	-5.05	-5.62	0.043	0.271
110	-9.87	-7.76	1.211e-6	0.519
120	-8.87	-9.58	0.657	0.162
130	-13.09	-14.35	0.785	0.219

Table 3. Statistical analysis of differences in the patellar tendon angle (PTA) between the ACLD and ACLI patient groups for the step-up and forward lunge exercise at different knee flexion angles (KFA). Lines highlighted in grey represent a p value below 0.05.

KFA (degrees)	BP (mm)		*p*-value	Effect size
	ACLD	**ACLI**		
Step-up				
0	-5.57	-6.24	0.838	0.256
10	-3.44	-5.75	0.011	0.545
20	-6.71	-7.45	0.034	0.241
30	-4.73	-7.62	0.009	1.234
40	-3.36	-5.08	0.112	0.494
50	-6.24	-5.22	0.080	0.385
60	-2.71	-3.92	0.393	0.858
70	-1.22	-2.33	0.005	1.143
80	-1.08	-2.57	0.008	0.425
90	-1.13	-2.95	7.483e-5	0.586
Knee Bend				
90	-1.31	-3.14	4.134e-9	0.678
100	-1.53	-3.34	1.032e-8	0.780
110	-2.91	-3.08	0.026	0.159
120	-4.02	-7.95	5.722e-5	1.514
130	-9.88	-	-	-

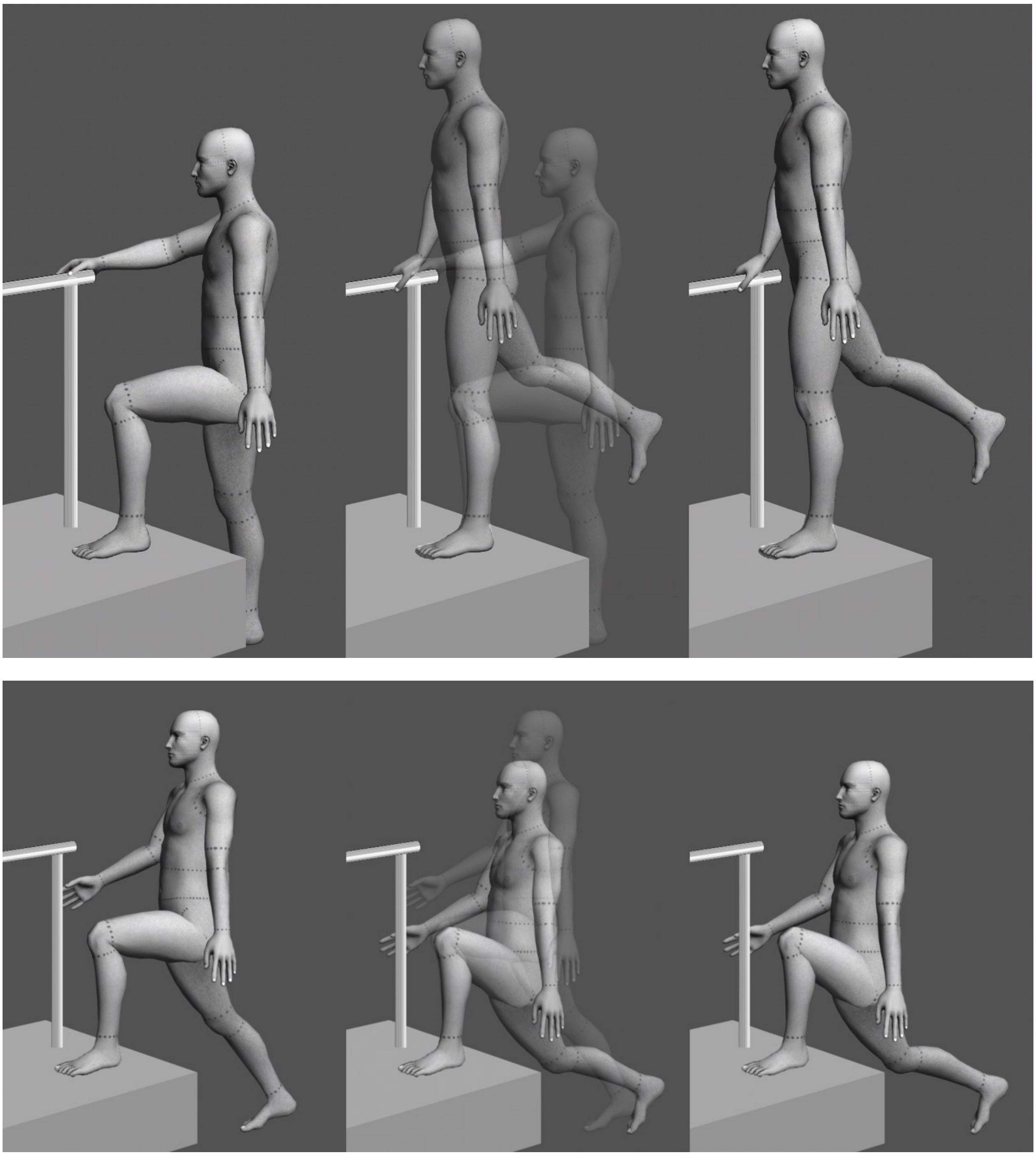
Table 4. Statistical analysis of the differences in bearing position (BP) between the ACLD and ACLI patient groups for the step-up and forward lunge exercise at different knee flexion angles (KFA). Lines highlighted in grey represent a p value below 0.05.

Exercise	Group	Exercise Time (s)	Range	*p*-value
Deep knee bend	**ACLD**	11.6	7.8-17.3	0.0012
	ACLI	8.0	4.0-15.5	
Step-up	**ACLD**	9.8	7.5-14.5	0.0007
	ACLI	7.5	5.1-10.0	

Table 5. Comparison of the mean time required to perform the forward lunge and step-up exercise for the different patient groups. Lines highlighted in grey represent a p value below 0.05.

Measurement	Intraclass Correlation Coefficient	Lower CI	Upper CI
PTA	0.968	0.945	0.982
BP	0.964	0.931	0.981

Table 6. Intraclass Correlation Coefficient values calculated for the PTA and BP, where two repeats were performed by one rater. The upper and lower confidence intervals (CI) for the coefficients are presented.



(a)

(b)

Figure 1. Illustration of (a) the step-up activity and (b) the deep forward lunge activity. Graphics created with PoseTool3D software (www.alienthink.com/posttool.blogspot.html).

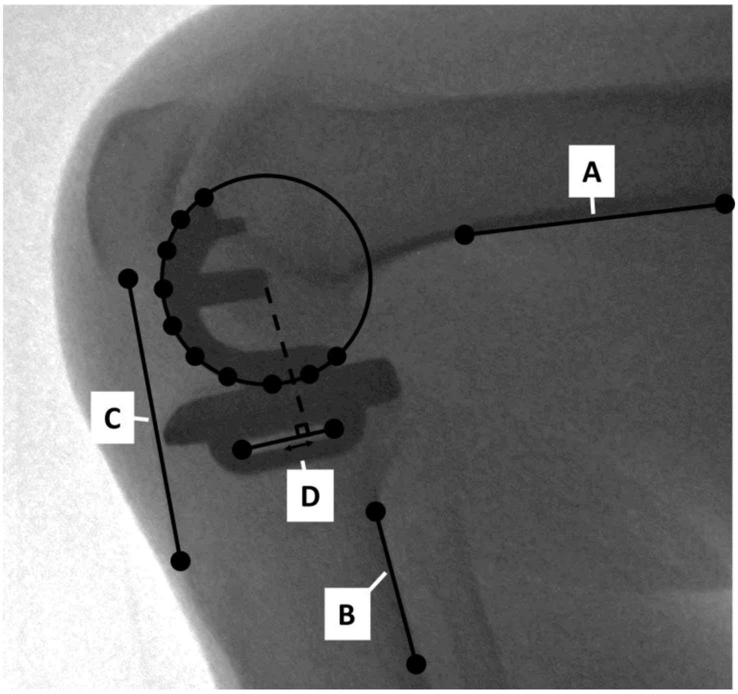


Figure 2. Landmark points selected by the user (black dots) enabled calculation of the femoral (A) and tibial (B) axes used to calculate the flexion angle, the patellar tendon axis (C) used to calculate the patellar tendon angle, and the bearing position (D).

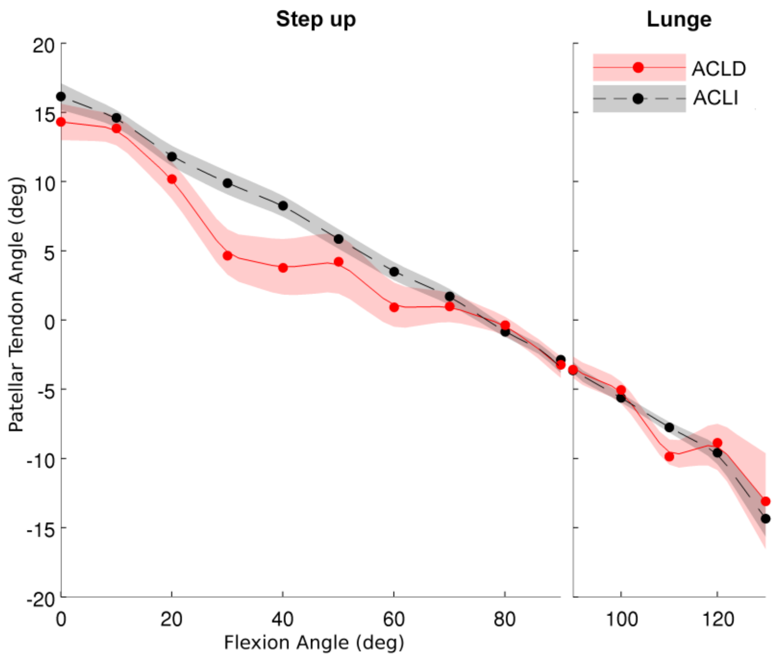


Figure 3. Relationship between patellar tendon angle and knee flexion angle for the step-up (0-90°) and forward lunge (90-130°) exercises; results for the ACLD and ACLI patient groups were compared. The shaded areas indicate the 95% confidence intervals.

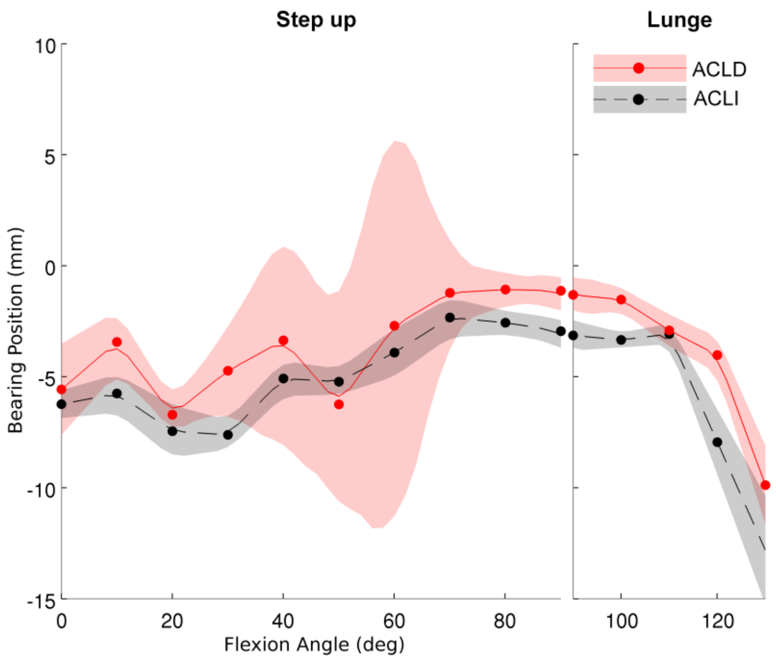


Figure 4. Relationship between bearing position and knee flexion angle for the step-up and forward lunge exercises; results for the ACLD and ACLI patient groups were compared. The shaded areas indicate the 95% confidence intervals. Positive BP denotes anterior bearing position, negative BP denotes posterior positioning.

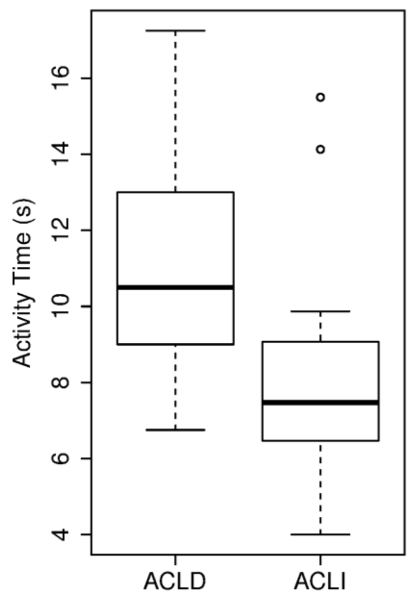


Figure 5. Boxplot of the time taken for the ACLD and the ACLI patient groups to perform the exercises; data shown is for both the step-up and the forward lunge results combined.