How effective are added constraints in improving TKR kinematics?

B.H. van Duren\textsuperscript{a, b}, H. Pandit\textsuperscript{a, c}, D.J. Beard\textsuperscript{a}, A.B. Zavatsky\textsuperscript{b}, J.A. Gallagher\textsuperscript{a}, N.P. Thomas\textsuperscript{c}, D.T. Shakespeare\textsuperscript{d}, D.W. Murray\textsuperscript{a}, H.S. Gill\textsuperscript{a,*}

\textsuperscript{a}Nuffield Department of Orthopaedic Surgery, Botnar Research Centre, Nuffield Orthopaedic Ctr, University of Oxford, Oxford, OX3 7LD, UK
\textsuperscript{b}Department of Engineering Science, University of Oxford, UK
\textsuperscript{c}Hampshire Hospital, Basingstoke, UK
\textsuperscript{d}Warwickshire Nuffield Hospital, Leamington Spa, UK

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Abstract

Newer designs of total knee arthroplasty (TKA), through the use of added degrees of constraint, attempt to provide a “guided motion” to restore more normal and predictable kinematics. Two such design philosophies are the posterior stabilised (PS) using a cam–post and the medial pivot (MP) concepts.

Knee kinematics of 12 patients with a PS TKA, 13 subjects with a MP TKA and 10 normal subjects were compared. For kinematic assessment, patients underwent fluoroscopic assessment of the knee during a step-up exercise and deep knee bend. Fluoroscopic images were corrected for distortion and assessed using 3D model fitting to determine relative 3D motion, and a 2D method to measure the patellar tendon angle (PTA) as function of knee flexion.

For the PS design the cam–post mechanism engaged between 70° and 100° flexion. Between extension and 50° there was forward motion of the contact points. Beyond 60° both condyles rolled moved posteriorly. The majority of the external rotation of the femur occurred between 50° and 80°. The PTA was lower than normal in extension and higher than normal in flexion.

The MP exhibited no anterior movement throughout the range of motion. The medial condyle moved minimally. The lateral contact point moved posteriorly from extension to flexion. The femur rotated externally throughout the range of flexion analysed. The PTA was similar to normal from extension to mid flexion and then higher than normal beyond to high flexion.

The PS design fails to fully restrain paradoxical anterior movement and although the cam engages, it does not contribute significantly to overall rollback. The MP knee does not show significant anterior movement, the medial pivot concept appears to achieve near normal kinematics from extension to 50° of knee flexion. However, the results show that at high flexion this design does not achieve normal knee kinematics.

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1. Introduction

Traditional total knee arthroplasty (TKA) designs exhibit highly variable and often grossly abnormal kinematics. A common feature is subluxation of the femur posteriorly in extension and sliding forward in flexion; a disparity most apparent when patients attempt to perform strenuous activities that place large demands on the knee joint (Conditt et al., 2004). It is thought that this abnormality is due to the inability of some TKA designs to provide adequate stability and/or induce sufficient femoral rollback with progressive knee flexion. Femoral rollback has a potential advantage of improved knee flexion and increased quadriceps moment arm. Newer designs of TKA, through the use of added degrees of constraint, attempt to overcome these problems by providing “guided motion”. It is hypothesised that restoring more normal and predictable kinematics will improve functional outcome. Two different design philosophies for obtaining guided motion are the cam-post and the medial pivot concepts.

*Corresponding author. Tel.: +44 1865 227457; fax: +44 1865 227671. E-mail address: richie.gill@ndos.ox.ac.uk (H.S. Gill).
The concept of the cam-post mechanism was introduced in late 1970’s (Insall et al., 1982), with the aim of generating femoral rollback. It incorporates a cam within the femoral component which mechanically interacts with a post extending from the tibial insert. The construct is designed to replicate the function of the posterior cruciate ligament (PCL) and is intended to provide femoral rollback by virtue of the cam engaging the post and guiding the femur posteriorly along the tibia with progressive knee flexion. This concept is also termed PCL-substituting (PS).

Later studies investigating normal knee kinematics (Iwaki et al., 2000; Blaha et al., 2003) led to the development of a medial pivot (MP) knee design concept. The MP TKA concept features a highly congruent femoral-articular surface interface on the medial side approximating a ball and socket joint, and a less congruent lateral articulation permitting the lateral condyle to roll and slide posteriorly.

In a previous fluoroscopic study (Pandit et al., 2005) we compared the sagittal plane kinematics of a PCL-retaining TKA (termed cruciate-retaining or CR) to that of a PCL-substituting TKA (Scorpio knee system, Stryker, Newbury, UK). In that study, we assessed the planar motion of the femur relative to the tibia using the patella tendon angle (PTA) through the range of knee flexion (0–90°). The PTA is the angle subtended between the patella tendon and the tibial axis (Pandit et al., 2005), and PTA plotted against knee flexion angle (KFA) is termed the kinematic profile. PTA is an indicator of overall knee joint kinematics since it is dependent upon the orientation of the patella and the relative positions of the femur and tibia. The kinematic profiles were abnormal for both designs and no significant difference was found between the kinematics of the CR and PS design variants. This finding suggested that the cam-post mechanism in this design was ineffective in achieving femoral rollback.

The question as to why this design of cam-post mechanism is ineffective then arises. It may be that the mechanism does not engage at all. As our previous 2D method cannot determine if this is the case, a new method of examination is required. Furthermore, it is useful to compare the two different guided motion concepts with a combination of our previous and new measurement methods in order to evaluate whether the medial pivot concept is effective. The aim of the current study was to examine TKA kinematics in 3D in order to answer the above two questions.

2. Methods

2.1. Patients

The local ethics committee approved the study and each patient gave informed consent before participation. Twelve patients who had received a Scorpio PS knee arthroplasty at least 12 months prior to assessment were recruited. The patella was resurfaced in every case, the average age of the PS group was 72.4 years (range: 64–78 years). Similarly, 13 patients who had received an advance medial pivot knee arthroplasty (AMP, Wright Medical Technology, Memphis, USA) at least 12 months prior were also recruited. Of these, all but two had resurfaced patellae, the average age of the MP group was 75.2 years (range: 68–78 years). All patients had either excellent or good outcome according to the American Knee Society Scoring system.

2.2. Data acquisition and analysis

Kinematic data were obtained using our standard fluoroscopic technique (Pandit et al., 2005). Immediately prior to each measurement a reference object consisting of two planar grids of radio-opaque markers was imaged. Each patient was instructed to perform a single step-up exercise and a weight bearing deep knee bend. For the step-up exercise, the foot of the limb to be examined was positioned on a platform 250 mm high with the other foot on the ground such that the implanted knee was flexed to approximately 80°. Patients were allowed to touch a side bar for stabilisation. They were instructed to rise up from the initial position as if progressing to another step and fluoroscopic data acquired. Fluroscopy images were recorded as the exercise was performed. This exercise was chosen as it is a high-demand functional activity for TKA patients and has been previously validated (Pandit et al., 2005). To obtain data at higher flexion angles the deep knee bend was used. From the same initial position patients were instructed to lower themselves towards the floor by flexing the support knee, causing the implanted knee to flex up to approximately 110°.

Images were sampled at 25 frames per second, ensuring that the knee remained in the fluoroscopy field throughout the exercise. For each recording the plane of the fluoroscopic image was aligned parallel to the sagittal plane of the knee. The fluoroscopic images were recorded digitally in DICOM format.

Each image frame was converted to TIFF format using Matlab (version 7.0, The MathWorks, Massachusetts USA). Fluoroscopic images contain both pin-cushion and s-curve distortions (Baltzopoulos, 1995), these were corrected individually for each patient. From the captured data of the reference grids, the coefficients for image distortion correction were calculated using a global correction method (Baltzopoulos, 1995). Distortion correction was then performed for all subsequent frames. In addition, as the reference object was three dimensional, a projection matrix mapping the three-dimensional coordinates of the measurement volume to the two-dimensional coordinates of the corrected image was calculated (Mery, 2003); this mapping was unique for each measurement session. This mapping provided the basis of modelling the fluoroscopic environment. Using geometric models (computer aided design or CAD models) of the implant components (obtained from the implant manufacturers), placed in the virtual measurement volume, it was then possible to generate a silhouette projected onto the virtual fluoroscopic image plane; this was termed a synthetic silhouette. By adjusting the position of the model components in virtual space, the synthetic silhouette was fitted to the silhouette seen in the real distortion-corrected fluoroscopic images using the image matching algorithm proposed by Mahfouz et al. (2003). A random search algorithm, similar to that described by Spall (2004), was used to minimise the mismatch between synthetic and real silhouettes by optimising the orientation and position of the virtual components; the optimised orientations and positions were taken to be those of the actual components.

To test the accuracy of the method a phantom was constructed which allowed in-plane translation, out-of-plane translation (in-plane being parallel to the fluoroscope image plane, plane XY) and rotation of the femoral relative to the tibial component (Fig. 1). The phantom was constructed using Perspex on account of its radiolucent properties. To simulate in-plane X and Y translations, four different fittings were accurately machined (using a CNC machine tool) at prescribed translations relative to each other (Fig. 1A). These same fittings were used for out-of-plane translations by means of rotating the phantom through 90°. Four different positional fittings were also machined for the in-plane rotations (Fig. 1B) and similarly for out-of-plane rotations (Fig. 1C) by rotating the phantom through 90°. For each of the possible phantom
configurations a series of three measurements was performed giving a total of 48 sets of error determinations. The average errors in X, Y and Z translational directions were 0.15, 0.00 and 0.47 mm with standard deviations (SD) 0.55, 0.69 and 5.11 mm, respectively. In the X, Y and Z rotational degrees of freedom the errors were −0.1° (SD: 0.83°), −0.52° (SD: 1.99°) and −0.03° (SD: 2.88°). The accuracy test results for the system were similar to those published in the literature (Banks and Hodge, 1996; Hoff et al., 1998; Zuffi et al., 1999; Mahfouz et al., 2003).

2.3. Determining contact points and Cam-post distance

Since the knee designs being studied had fixed bearings, knowledge of the orientation and position of the tibia enabled the orientation and position of the tibial insert surface to be determined. Thus, it was possible to determine the relative in vivo motion of the femoral component with respect to tibial insert surface during function activities. To determine the point of contact between the femoral component and the tibial insert, the articulating surfaces of both components were described as point clouds. In order to obtain a high-resolution description, these surfaces were first finely meshed using MSC.Patran 2005 (MSC Software Corporation, CA, USA), and then the nodes exported in a neutral format to serve as point cloud descriptions (Fig. 2). These coordinates were then transformed into a tibia fixed coordinate system for each frame of measured functional activity. A closest points algorithm was used to determine if, and where, contact was occurring between the femoral surface and the tibial insert surface in the medial and lateral compartments as well as between the femoral cam and tibial post. For the PS knees, the absolute distance between the closest points on the cam and post was determined and recorded; the cam–post mechanism was considered to be engaged if the minimum distance between the two was 0.5 mm or less. For both designs of TKA, the contact positions on the tibial insert surface for the medial and lateral femoral condyles were expressed relative to the mid-coronal plane of the tibial component and normalised to the tibial tray’s maximum dimension in the sagittal plane; this dimension was termed \( w \) (see inset Figs. 4 and 6) and contact point motion described as a percentage of \( w \) (\%\( w \)), with the anterior edge at 50\%\( w \), the posterior edge at −50\%\( w \) and the mid-coronal plane taken to be at 0\%\( w \). Contact positions anterior to the midline were denoted as positive.

2.4. Kinematic profile

The kinematic profile has been previously defined as the relationship between the PTA and the KFA (Pandit et al., 2005). For each frame of recorded functional activity, the femoral and tibial axes, tibial tubercle and the distal pole of the patella were determined interactively using a graphical user interface developed using Matlab (version 7, The Maths Works Inc., Natick, Massachusetts). The tibial long axis was defined as the posterior border of the tibia (van Eijden et al., 1985) and the femoral long axis as the posterior border of the lower diaphysis of the femur (Rees et al., 2002). The angle between the two axes was taken as the KFA. The PTA was calculated using the line subtended between the tibial tubercle and the distal pole of the patella, and the tibial axis. The kinematic profiles of the two TKA designs were compared to a group of 10 normal asymptomatic knees (mean age 37 years, range 27–42 years). The PTA data were interpolated to give data points at every 10° of KFA throughout the flexion range. Differences between the PS, MP and normal groups

Fig. 1. Illustration of the validation rig used in the in vitro validation experiments. The rig allows planar displacement of components (A) and in-plane rotations (B), as well as out of plane rotations (C).

Fig. 2. Figure showing the CAD geometry of the implant components (A). Once the position of the tibial component has been determined the position of the tibial insert with respect to the femur can be determined (B) and then high definition descriptions of the cam and the post used (C) post: 1500 points and cam: 1000 points to determine the shortest distance between the two.
were examined using t-tests at flexion angles of interest. Statistical analysis was performed using Matlab.

3. Results

3.1. Posterior stabilised group

3.1.1. Cam–post mechanism

The cam–post mechanism engaged for all but one of the patients analysed (Fig. 3). All engagements occurred between 70° and 100° of knee flexion. The average angle of engagement was 82° (SD: 16.1°).

3.1.2. Tibial–femoral contact points

For the functional activity of step-up, the knee goes from flexion to extension, for the PS knees the mean tibial–femoral contact points remained posterior to the mid-coronal plane throughout the range of knee flexion (Fig. 4). The lateral condyle contacted the tibia near its posterior edge (−30%w) at high flexion, whilst the medial condyle contact was closer to the midline (−15%w) at the same extreme of the flexion range. As the knee extended, both condyles moved anteriorly, with the medial condyle approaching the midline at approximately, 60° KFA and then the contact moved posteriorly as the knee further extended. Near extension the medial condyle contact was at approximately −12%w. The anterior movement of lateral condyle occurred at a similar rate to that of the medial condyle from 100° to 70° KFA, the most anterior position (−9%w) was obtained at 40° KFA; there was internal rotation of the knee from 70° to approximately 40° KFA. For the remainder of extension, the lateral condyle moved posteriorly at a similar rate as the medial condyle, with no significant rotation. The overall excursion for the lateral condyle was 25.2%w, compared to 16%w for the medial condyle. The maximum knee flexion achieved during the deep knee bend activity was 91.2° (SD: 10°).

3.1.3. Patella tendon angle

The mean PTA of the PS knees was −1.1° (SD: 3.0°) at 100° of knee flexion and this increased to 10.5° (SD: 3.3°) at full extension (Fig. 5). The change in PTA with KFA was not linear, the gradient being steeper between 100° and 80° of knee flexion than for the remainder of the flexion range. The PTA of the PS knee was greater than that of the normal knee in flexion and less than normal in extension; the difference from normal was significant (p < 0.05) for KFA values between 80° and 100°.

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Fig. 3. Distance between the closest points on the cam and post plotted against KFA for the posterior stabilised knees.

Fig. 4. Medial and lateral contact point motion against knee flexion angle for the PS knee group. Motion is given as %w, where w is the maximum anterior–posterior dimension of the tibial tray, as shown by inset diagram.
3.2. Medial pivot group

3.2.1. Tibial–femoral contact points

As for the PS knees, the mean contact points for the MP knees remained posterior to the mid-coronal plane throughout the range of knee flexion, but there was a markedly different pattern of contact point motion. The medial condyle exhibited no significant change in contact position throughout the flexion range, staying at approximately $-7\%w$ (Fig. 6). The lateral condyle contact point was at $-31.9\%w$ (SD: 11.27\%w) at 110° KFA, as the knee extended it moved anteriorly to $-4.0\%w$ (SD: 7.5\%w), with the knee internally rotating as it extended throughout the flexion range. The overall excursion for the lateral condyle was 28.0\%w, compared to 3.5\%w for the medial condyle. The maximum knee flexion achieved during the deep knee bend activity was 99.3° (SD: 10.1°).

3.2.2. Patella tendon angle

The PTA of the MP knee ranged from 0.6° (SD: 2.3°) at 110° KFA to 13.2° (SD: 4.45) at full extension (Fig. 6). From full flexion to 50° KFA the PTA of the MP knee was greater than that for the normal knees, significantly greater ($p<0.05$, t-test) from 100° to 80° KFA. Between 50° to full extension the PTA of the MP was similar to that of the normal knee.

4. Discussion

Fluoroscopic motion analysis using a computer modelling-fitting technique is an established and increasingly popular method for accurately measuring the 3D in vivo kinematics of total knee arthroplasty. The majority of these systems look at the medial and lateral femoral–tibial contact points at various degrees of knee flexion usually under weight bearing conditions (Banks and Hodge, 1996; Stiehl et al., 1997; Hoff et al., 1998; Zuffi et al., 1999; Mahfouz et al., 2003). In addition to determining the medial and lateral condylar contact points we used our system to determine if and when the cam and post engaged. As well as using the motion of the contact points to quantify in vivo tibio-femoral kinematics, we also assessed the overall knee kinematics using the PTA/KFA relationship or kinematic profile. The PTA provides a useful global picture of the mechanical function of the knee as it is influenced by tibial–femoral and patellar–femoral movement (Gill and O’Connor, 1996; Miller et al., 1998; Price et al., 2004; Rees et al., 2005). There are distinct advantages of analysing PTA/KFA and cam–post interaction together with the analysis of the 3D contact points. The calculation of contact points is highly dependent upon the surface geometry of both the femoral component and the tibial insert; thus small changes in geometry may be interpreted as gross changes in kinematics. As the overall kinematics of the joint are reflected in the PTA/KFA relationship, it is not influenced by numerical effects of contact point calculation.

The purpose of the current study was to evaluate whether the additional constraints included in two different TKA designs were effective in achieving more normal kinematics. Kinematic analyses have determined several kinematic differences between knee replacement and normal knees. It has been reported that TKA results in changes to the relative tibio-femoral sagittal plane displacement, axial rotation of the knee joint, decreased maximum flexion and femoral condylar lift off (Dennis et al., 2003).

In this study the medial pivot knees achieved, on average, a higher KFA than the posterior stabilising knees during the lunge activity. Given the small numbers involved in this study, the significance of this finding is questionable, but it is not supported by (Shakespeare et al., 2006) who reported no significant difference between the maximum flexion achieved by a posterior substituting design and a MP.

Anterior femoral translation has a negative effect on the kinematics and kinetics of the knee, as well as the wear...
properties of an implant. An anteriorly positioned femur on the tibia can limit the maximum knee flexion achieved, due to impingement posteriorly. At high flexion angles, an anterior displacement of the femur can reduce the effective quadriceps’s moment arm. Sliding of the femoral component on the polyethylene articular surface can lead to increased wear. In the current study, the functional activity measured involved the knee moving from flexion to extension; however, it has become the convention to discuss knee kinematics as a function of increasing KFA, hence in the remainder of this discussion this extension to flexion convention will be used. Between 0° and 50° of flexion the PS knee displayed what has become termed “paradoxical anterior movement” of the contact points. Subsequently, from 60° to maximum flexion the contact points of both condyles then moved posteriorly. This is interesting, as cam–post engagement was observed to occur on average at 80° of knee flexion. Therefore, the initial rollback cannot be explained by the cam–post mechanism. The cam–post mechanism may be providing a contribution to rollback above 80° of flexion, as there is a change in the gradient of the kinematic profile for the PS knees at this value of KFA (Fig. 5). The rollback pattern observed in the PS knee is different to that reported for the normal knee (Asano et al., 2001; Dennis et al., 2005); in the normal knee the medial contact point undergoes minimal rollback, whilst the PS knee both condyles display substantial rollback.

The MP in contrast to the PS does not show any paradoxical anterior movement of the contact points with the medial contact point moving minimally acting as a pivot and the lateral moving posteriorly with flexion. The gradient of the posterior movement of the lateral contact point with KFA is not constant; there is an increase in gradient beyond 90° of flexion. The minimal medial contact point movement and constant posterior translation of the lateral contact point is similar to that reported for normal knees (Asano et al., 2001; Dennis et al., 2005).

It is clear from the kinematic profile curves (Fig. 5) that neither knee arthroplasty design achieves normal kinematics. The PTA of the PS knees is lower than normal in extension and higher than normal in flexion. The PS device fails to match normal kinematics for any part of the flexion range; the MP design is close to normal from extension to 50° flexion. At flexion angles above 50° the kinematics of PS device, whilst not normal, are closer to normal than the MP. Both devices fail to achieve a normal pattern of rollback, and even when the cam–post mechanism of the PS design is engaged it still displays highly abnormal kinematics. It should be noted that given the measurement error and the criterion chosen for assuming contact, there is a degree of uncertainty in determining when the mechanism has engaged. The higher PTA values during high flexion for the MP device indicate insufficient posterior movement of the femur on the tibia; modifying the radius of the femoral component and the placement of the medial rotation point on the tibia may improve this.

In summary, the present study has used a combination of 3D kinematic fluoroscopy reconstruction and PTA to assess the functional kinematics of a posterior stabilised TKA and a MP TKA. The PS design fails to prevent paradoxical anterior movement and although the cam engages in flexion, it does not contribute significantly to initial rollback and increased rollback occurs too late in flexion. Additionally, when recent studies of normal knee kinematics are considered, the large amount of medial condyle movement is abnormal and has the potential to permit increased instability. The cam–post mechanism is ineffective in generating physiological rollback, even though it engages; this raises some concern regarding stress levels in the polyethylene post. The MP knee rotates externally about the medial condylar axis as intended by design and does not show any significant paradoxical anterior movement. The guided motion provided by the MP appears effective in achieving near normal kinematics from extension to 50° of knee flexion. The conformity of the medial compartment confers stability and will give rise to lower stresses in this part of the polyethylene bearing. However, the results show that at high flexion this design does not achieve normal knee kinematics, suggesting that the design parameters may not be fully optimised for high flexion.

References


