Influence of surface geometry and the cam-post mechanism on the kinematics of total knee replacement

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Abnormal sagittal kinematics after total knee replacement (TKR) can adversely affect functional outcome. Two important determinants of knee kinematics are component geometry and the presence or absence of a posterior-stabilising mechanism (cam-post). We investigated the influence of these variables by comparing the kinematics of a TKR with a polyradial femur with a single radius design, both with and without a cam-post mechanism.

We assessed 55 patients, subdivided into four groups, who had undergone a TKR one year earlier by using an established fluoroscopy protocol in order to examine their kinematics *in vivo*. The kinematic profile was obtained by measuring the patellar tendon angle through the functional knee flexion range (0° to 90°) and the results compared with 14 normal knees. All designs of TKR had abnormal sagittal kinematics compared with the normal knee. There was a significant ($p < 0.05$) difference between those of the two TKRs near to full extension. The presence of the cam-post mechanism did not influence the kinematics for either TKR design. These differences suggest that surface geometry is a stronger determinant of kinematics than the presence or absence of a cam-post mechanism for these two designs. This may be because the cam-post mechanism is ineffective.

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Joint kinematics are being increasingly studied as they are among the many factors which might influence the outcome after total knee replacement (TKR). In the belief that a more normal pattern of movement can provide the best outcome, manufacturers have sought to reproduce the form and function of various anatomical structures in the knee. In particular, the shape of the prosthetic components and their ability to compensate for lost or impaired ligament function, are two issues deemed to influence greatly the kinematics of TKR. Specifically, the geometry of the femoral component, and the decision whether to retain, sacrifice or replicate the posterior cruciate ligament (PCL), have raised considerable controversy.[1]

We aimed to establish the relative influence of both femoral geometry and sacrifice or retention of the PCL by assessing the *in vivo* kinematics in the sagittal plane of two different designs of TKR, which differed primarily in the geometry of the femoral component. However, because of their availability in both PCL-retaining and PCL-substituting forms, the influence of sacrifice or retention of the PCL was also investigated by using a four-group experimental design.

The PFC-Sigma (DePuy; Johnson and Johnson, Leeds, UK) has a traditional polyradial femoral component with a varying rotational axis, while the Scorpio (Stryker SA, Montreux, Switzerland) has a single-axis, single-radius femoral component. The latter is claimed to improve the quadriceps lever arm by using the transepicondylar axis as its only axis of rotation. The geometry of the tibial inserts differs between the two devices. The sulcus of the Scorpio is positioned more posteriorly than for the Sigma, while the Scorpio's insert is said to allow almost double the rotation. For both designs no major differences exist between the femoral articular geometry for either the cruciate-retaining or posterior-stabilised variants. For the tibial inserts of both designs, the posterior-stabilised variants are slightly deeper-dished. For the Scorpio, the tibial insert is also more steeply inclined at its anterior lip for the cruciate-retaining variant compared with its posterior-stabilised form.

The philosophy of cruciate-retention assumes that the PCL retains some function in the absence of the anterior cruciate ligament (ACL). It is suggested that the PCL has a beneficial effect on femoral rollback, range of movement, quadriceps efficiency, joint stability, and on reducing tibial shear forces.[2-9] The philosophy of cruciate-sacrifice questions the function of the PCL in isolation, but acknowledges the need for posterior stabilisation and uses the cam/post mechanism to replicate the physiological functions of the PCL.[8]

Evaluation of the complete kinematics of the knee is complex as it comprises two three-dimensional (3D) joints, each having 6° of freedom. In this study we examined the kinematics in the sagittal plane where the majority of functional activities occur. They were described by an established technique in which the relationship between the patellar tendon angle (the angle between the patellar tendon and the tibial axis) and the angle of knee flexion is quantified; this relationship is called the kinematic profile. The patellar tendon angle is a good measure of both patellofemoral and tibiofemoral joint kinematics[10-13] and is related to both the patellofemoral[10,13] and the tibiofemoral contact forces. It depends primarily on the interactions of surface geometry between the femur and tibia and the shapes of the patellar surface and trochlear grove. Major abnormalities in the patellar tendon angle are likely to be a result of abnormalities in the relationship of the femur to the tibia. Anterior subluxation of the femur increases the angle whereas posterior subluxation decreases it.

We wished to compare the kinematic profiles for each of the four designs of TKR during three separate functional exercises. We considered that any observed differences would indicate the relative influence of femoral geometry and PCL sacrifice or retention.

Patients and Methods

Patients with an underlying diagnosis of osteoarthritis and excellent clinical performance at least one year after TKR, as assessed by the American Knee Society score (AKSS),[14] were included. The local ethics committee approved the study and each patient gave informed consent before participation.

A total of 55 patients underwent *in vivo* kinematic assessment using an established fluoroscopic technique.[11] They were recruited from an ongoing larger randomised controlled trial comparing the Scorpio and PFC-Sigma designs, and were further randomised according to their cruciate-retaining or posterior-stabilised configuration. Thus, the study group was divided into four subgroups: group I, Scorpio (cruciate-retaining; n = 13); group II, Scorpio (posterior-stabilised; n = 14); group III, Sigma (cruciate-retaining; n = 14) and group IV, Sigma (posterior-stabilised; n = 14). The groups were well matched for age, gender and operating surgeon (Table I).

Table I. Patient demographics for the different groups

Implant group	Prosthesis	Mean age in yrs (SD)	Gender*
I	Scorpio (cruciate-retaining)	70.1 (5.2)	6M, 7F
II	Scorpio (posterior-stabilised)	71.2 (4.9)	6M, 8F
III	Sigma (cruciate-retaining)	69.5 (3.7)	5M, 9F
IV	Sigma (posterior-stabilised)	70.2 (4.5)	6M, 8F

* M, male; F, female

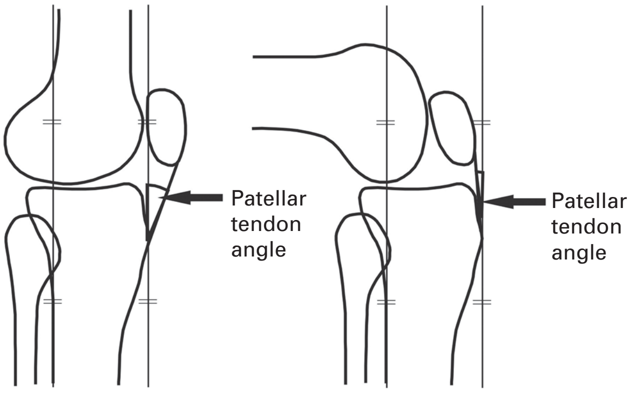

Fig. 1a

Fig. 1b

The patellar tendon angle is the angle between the long axis of the tibia and the patellar tendon. Figure 1a – The figure indicates how the angle is positive with the knee extended. Figure 1b – Becomes negative as the knee flexes.

Surgical technique. A standard surgical technique was used. All operations were performed by surgeons with a high level of experience and according to the manufacturer's recommendations. The surgical findings were carefully recorded in a standard way. This included the extent of any soft-tissue release, the status of both the ACL and the PCL at the start and end of surgery, femoral and tibial alignment, and the tibial slope used to cut the tibia. The patella was always resurfaced with a patellar button. All TKRs for this study were cemented using CMW1 cement with gentamicin (DePuy, Johnson and Johnson).

Clinical and radiological assessment. An independent, blinded observer assessed all the patients before surgery and one year post-operatively. The AKSS (clinical and functional)[14] and the Bartlett patellar score[15] were obtained at each assessment. Post-operative radiographs were assessed using the AKSS system.

Kinematic assessment with fluoroscopy. For kinematic assessment, patients underwent fluoroscopy in order to allow measurement of the patellar tendon angle at various degrees of knee flexion (Fig. 1). The patellar tendon angle can be reliably measured with sagittal plane video fluoroscopy.[16,17] The relevance of the patellar tendon angle as a kinematic variable has been well validated and is outlined by Price et al.[11]

Fluoroscopy. We used a standard fluoroscopy technique (Siemens Angiostar, Siemens Medical, Berkshire, UK) technique[11] for the assessment of knee kinematics. Fluoroscopic axis views were obtained at the beginning of each study. These comprised exposures of the distal half of the femur and the proximal half of the tibia of the operated knee. The views were subsequently used as a baseline in order to define the femoral and tibial axes. Patients then performed three different exercises, chosen to give the ranges of relative tibiofemoral position and to include a high-demand functional activity. Patients were allowed to practise the exercises until they were confident with each one.

Exercises. Exercise A was active knee extension against gravity. Patients were examined in a semi-supine position, moving their knee from 90° of flexion to full extension. The femur was supported in order to reduce rotation. Exercise B was active knee flexion against gravity. Patients were examined standing up. The femur remained perpendicular to the floor and the patients flexed the knee against gravity, moving from full extension (0°) to 90° of flexion. Exercise C was a single step-up exercise. Patients placed the foot of the limb to be examined onto a platform 250 mm above their standing position, with the knee flexed to approximately 70°. Patients were allowed to touch a side bar for stabilisation. They were instructed to rise up as if they were going to progress to another step. Fluoroscopy was then recorded as they stepped up onto the platform. This test was chosen because it is a high-demand functional activity and has been used previously to demonstrate kinematic differences with a variety of knee replacements.[1] Video fluoroscopy was then undertaken, images being 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. Subsequently, individual frames were digitally sampled at approximately 10° intervals with a commercial frame grabber and software (MiroDV, Pinnacle Systems, Mountain View, California and Adobe Premiere, Adobe Systems Inc, San Jose, California).

Image analysis. Using the initial images, the femoral and tibial axes were identified. The tibial axis was defined as the posterior border of the tibia[12] and the femoral as the posterior border of the lower diaphysis of the femur.[18] The knee flexion angle was the angle between the tibial and femoral axes.

A graphic user interface was developed for this study using Matlab (version 6, The Maths Works Inc, Natick, Massachusetts) to calculate the patellar tendon and knee flexion angles.[19] This allowed us to correct for distortion[17] and to template the outlines of the tibia, femur and patella. The templates were scaled, rotated and translated to fit each image in subsequent frames. The relationship between the patellar tendon and knee flexion angles was termed the kinematic profile. We could then calculate this profile for each exercise over the entire range of knee flexion.

Assessment of error. Assessment was made of intra- and inter-observer error for the measurement of both patellar tendon and knee flexion angles. A series of 20 images from one exercise (one patient) was analysed by two observers in order to assess inter-observer error. The same images were subsequently reviewed by one of the observers for a second time in order to access intra-observer error.

Table II. Clinical outcome one year after surgery

	AKSS* (%)		
Implant group†	**Clinical (SD)**	**Functional (SD)**	**Bartlett patellar score[15] (%) (SD)**
I	*94.4* (5.3)	*80.2* (10.2)	*90.5* (5.7)
II	*93.2* (7.7)	*79.5* (6.8)	*89.5* (6.3)
III	*92.6* (10.1)	*81.2* (8.7)	*86.7* (8.7)
IV	*93.1* (8.4)	*77.8* (7.5)	*88.3* (7.8)

* AKSS, American Knee Society score[14]

† group I, Scorpio (cruciate-retaining); group II, Scorpio (posterior-stabilised); group III, Sigma (cruciate-retaining); group IV, Sigma (posterior-stabilised)

Sample size. Altman's[20] nomogram was used to calculate the sample size. Measurements of the patellar tendon angle for the step-up exercise, recorded at the mid-flexion range (40°), were considered most appropriate for the power calculation. A pilot study revealed the mean value for the normal group to be 12.2° (SD 3.1°). A difference of 4° between two groups was considered to be clinically relevant. The minimum sample size was calculated to be 11 in each group for a power of 80% with an alpha significance level of 0.05. Consequently, 13 patients were recruited for each group in order to ensure sufficient power. These measurements were compared with data from a group of 14 normal subjects, who were asymptomatic and pain-free, whose mean age was 28.2 years (24 to 35).

Statistical analysis. For each exercise a one-way analysis of variance (ANOVA) was used to examine the differences in patellar tendon angles for the normal and four knee replacement groups. Analysis was performed at three knee flexion angles, 10°, 40° and 80°, which are representative of the knee flexion angle during the functional activities of the stance phase in normal gait, midstair ascent and the start of a sit to stand manoeuvre, respectively. For the step-up exercise, 70° was used, as patients did not achieve higher values for this exercise. Any significant differences were further explored using a post-hoc Tukey test. Differences in functional scores between groups were also examined using a one-way ANOVA. A significance level of $p < 0.05$ was used throughout. Statistical tests were performed using SPSS version 11.5 (SPSS Inc, Chicago, Illinois).

Results

Clinical and radiological assessment. All patients had a good to excellent outcome as assessed by their AKSS and Bartlett patellar score (Table II). No significant difference was found between the four TKR groups. The post-operative radiographs showed satisfactory positioning of the components and alignment of the leg in all cases.

Analysis of fluoroscopic error. The standard deviation of inter-observer error for patellar tendon angles was 1.3° and 1.2° for knee flexion angles. For intra-observer error, the standard deviation was 1.3° for patellar tendon angles and 1.1° for knee flexion angles.

Kinematic profile. This showed a similar trend for all the three exercises. For the normal group, there was generally a

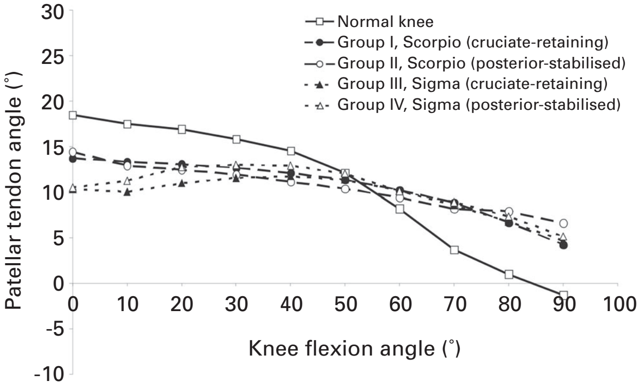

Fig. 2

Exercise A (extension against gravity) showing the kinematic profiles for the normal knee and the four TKR groups.

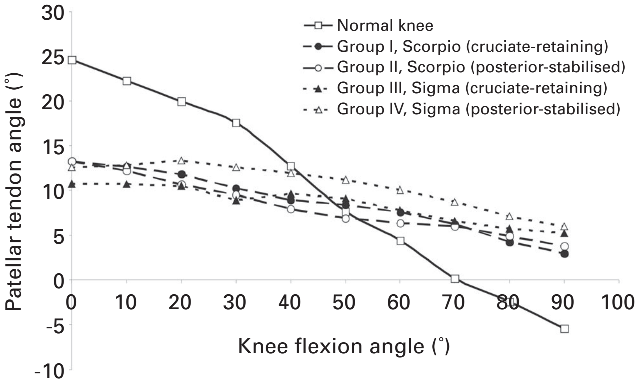

Fig. 3

Exercise B (flexion against gravity) showing the kinematic profiles for the normal knee and four TKR groups.

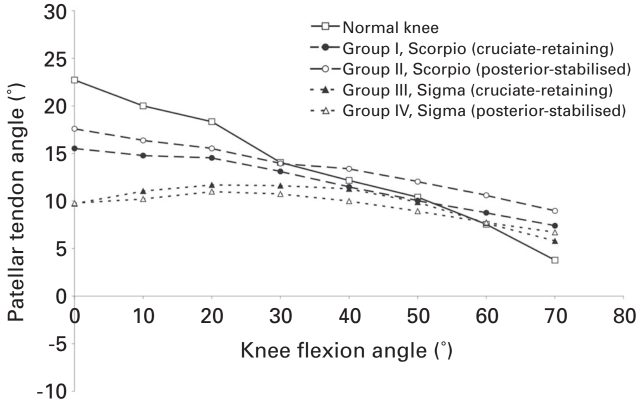

Fig. 4

Exercise C (step-up) showing the kinematic profiles for the normal knee and the four TKR groups.

linear decrease in patellar tendon angle which was high in extension and low or negative in full flexion. The kinematic profiles for the TKR groups were grossly different to the normal knee. The patellar tendon *versus* knee flexion angle curves for the TKR groups were essentially flat, showing a limited change in patellar tendon angles with progressive knee flexion (Figs 2 to 4).

Exercise A (extension against gravity). As the normal knee moved from flexion to full extension, there was an increase in patellar tendon angle, achieving a positive value between 80° and 90°. When knee flexion was more than 60° the patellar tendon angle for all the TKR groups was significantly higher than the normal group ($p < 0.001$). Groups I and II (Scorpio) showed a similar trend, but group II (Scorpio, posterior-stabilised) showed a greater variation throughout its range. Groups III and IV showed almost identical patterns. Both groups I and II (Scorpio) were closer to normal knee patterns than groups III and IV (Sigma) (Fig. 2).

Exercise B (flexion against gravity). For exercise B the normal group had a similar kinematic profile to exercise A. The kinematic profiles for all the TKR groups were essentially flat. The patellar tendon angle was significantly lower for the TKR groups in extension ($p < 0.001$) and significantly higher when the knee was flexed ($p < 0.001$), compared with the normal knee (Fig. 3).

Exercise C (step-up). The kinematic profile for the normal group was again similar to that for exercise A, but the overall values for the patellar tendon angle were higher. The variability between the groups was less pronounced than that seen in exercises A and B. All the TKR groups were significantly different from normal in extension ($p < 0.01$). As seen in exercise A, groups I and II (Scorpio) were closer to normal knee patterns than groups III and IV (Sigma) (Figs 2 and 4).

Overall, all the TKR groups exhibited very different kinematics from that of the normal knee. This was seen with all three exercises, mainly in extension and in high degrees of flexion; the flexion exercise (exercise B) showed differences throughout the range of knee flexion. There was no significant difference in the kinematic profiles between groups I and II (Scorpio cruciate-retaining and posterior-stabilised) and between groups III and IV (Sigma cruciate-retaining and posterior-stabilised). Thus, for each device the data for the cruciate-retaining and posterior-stabilised variants were combined to give a single Scorpio group and a single Sigma group for statistical analysis. The results from subsequent independent *t*-tests showed that for all exercises the kinematics of both groups were different in extension ($p < 0.05$). The Scorpio (group I and II) values for the patellar tendon angle were closer to those of the normal knee when near to full extension.

Discussion

For the normal knee, the relationship between the patellar tendon and knee flexion angles is almost linear. The patellar tendon angle is positive, and has its largest value, in full extension but decreases to a negative value when the knee is fully flexed. This was seen consistently for the three exercises. This kinematic profile reflects the functional behaviour of the extensor mechanism. A normal profile indicates that the natural relationships of the moment arm are maintained and that the muscles are operating optimally. Any abnormalities in the patellar tendon angle will result in abnormal muscle loads and joint contact forces. It is therefore reasonable to expect knee arthroplasties which have a close-to-normal kinematic profile to perform well, as the extensor mechanism will be functioning almost normally.

Intuitively, it would seem that normal kinematics after TKR should be associated with superior knee function, but the underlying explanation for abnormalities in the patellar tendon angle is not straightforward. Abnormalities in the patellofemoral joint such as an ‘over-stuffed’ patella or a shallow trochlea will result in small increases in the patellar tendon angle. In contrast, abnormalities in tibiofemoral kinematics may cause large changes in this angle. With a femur lying posteriorly on the tibia, the patellar tendon angle will decrease. Conversely, with a femur positioned anteriorly the angle will increase.

For both designs of TKR that we studied, the kinematic profiles were grossly abnormal, primarily because of abnormal tibiofemoral kinematics. In flexion, the patellar tendon angle for TKRs was greater than for the normal knee during all three exercises. However, in extension the patellar tendon angle for TKRs was less than for the normal, with differences also existing between the two designs.

While we expected the kinematics of unstabilised TKRs (non-cammed devices) to be somewhat abnormal, the values for the patellar tendon angle in the posterior-stabilised TKRs in flexion were unexpected; no differences were found between the cammed (posterior-stabilised) and non-cammed (cruciate-retaining) variants. This suggests that the cam-post mechanism does not function as it would force the femur backwards on the tibia and result in a decrease of patellar tendon angle. It may be argued that a closed chain exercise only examines knee flexion up to 70° and, therefore, late cam-post engagement may not be evident. Although closed chain exercises are representative of daily function, they are more a snapshot of joint kinematics in terms of anteroposterior tibiofemoral excursion and cam function. In contrast, open chain flexion against gravity and extension against gravity both represent extremes of anteroposterior tibiofemoral excursion and will give a polarised view of cam function. In these exercises the tibia is either pulled backwards by the hamstrings (flexion) or forwards by the quadriceps (extension). If the cam-post mechanism is engaging at all, and is effective in producing a femoral rollback at any angle of knee flexion up to 90°, there should be a sharp reduction in the patellar tendon angle in at least one of the open chain exercises. This was not the case for either the Scorpio or the Sigma groups.

Our findings may explain why earlier studies have not shown clinical differences between cruciate-retaining and posterior-stabilised devices. The abnormally high values for patellar tendon angle observed in flexion for both TKR designs could theoretically be brought closer to normal by modifying the cam-post mechanism. Although this might improve the kinematics, it may incur other risks such as wear.

The differences in patellar tendon angle between TKR designs in extension highlight the importance of geometry as a determining factor in joint kinematics. For each design the retention or sacrifice of the PCL did not alter the kinematics. Consequently, the differences in the patellar tendon angle in extension between the Scorpio and Sigma must be because of differences in their femoral and tibial geometry. Interestingly, the Scorpio was closer to normal in extension than the Sigma, especially when loaded as in exercise C, with step-up activity.

Significant differences existed between the Scorpio and Sigma knees for kinematics but not for clinical scores. This may be because joint function is independent of kinematics. Perhaps a more likely explanation is that our study had insufficient power to detect differences in clinical scores between the designs; approximately 500 patients would have been required to do this. There was some evidence of an association, as the design with kinematics which were closer to normal (Scorpio) had better clinical scores. In contrast with studies using clinical scores, analysis of the patellar tendon angle is a powerful method of investigating sagittal plane kinematics and requires a smaller number of patients.

Our study has shown that knee kinematics after TKR are grossly abnormal. It also examined the effect of two variables, namely component geometry and the presence or absence of a cam/post mechanism, on the kinematics. The similar kinematics exhibited by both cruciate-retaining and posterior-stabilised configurations suggests that the cam-post mechanism is ineffective in controlling the position of the femur in flexion. The differences found between the two contrasting designs suggest that surface geometry is a stronger determinant of knee kinematics than the presence or absence of a cam-post mechanism.

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