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ORIGINAL STUDY

Improving maximum flexion with a posterior cruciate retaining total knee arthroplasty : A fluoroscopic study

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Achieving a large range of motion (ROM) is a much-desired clinical outcome after total knee arthroplasty (TKA), especially in Asian and Middle Eastern cultures. TKA design plays an important role in providing the post-operative ROM. This study investigated the kinematics of a new high-flexion posterior cruciate ligament retaining total knee replacement, featuring an enlarged posterior condylar offset and a more conforming tibiofemoral articulation. Two flexion activities were compared to determine which provides higher flexion kinematics. Sixteen North American patients with 20 total knee implants were studied using fluoroscopy and shape matching techniques. Maximum skeletal flexion during a lunge activity averaged 120° ± 11°, with 11° ± 4° tibial internal rotation. Kneeling activities showed 11° greater average maximum skeletal flexion (131° ± 13°, $p < 0.05$) and 1° less tibial internal rotation (10° ± 4°, $p > 0.05$) than lunge activities. We conclude that specific knee implant design features can facilitate high flexion in fixed-bearing cruciate retaining TKA, and that kneeling activities provide higher flexion than lunge activities.

Keywords : total knee arthroplasty ; biomechanics ; fluoroscopy ; high flexion ; lateral pivoting.

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INTRODUCTION

With growing demands on the quality of life, the range of motion (ROM) after total knee arthroplasty (TKA) has become an important issue around the world (*12,17,27,35*). Historically, patients in Asia and the Middle East have required large ROM (111° to 165°) to perform religious and lifestyle activities (*24*). In Western Europe and North America 105° to 115° flexion has been considered satisfactory, but with younger patients and increasingly active senior citizens, there is a growing demand for greater ROM (*3,34*). Meeting these demands for increasing ROM after TKA remains a challenge (*17,20,28,31,33-39*).

Many different factors of the patient's treatment have an influence on the post-operative ROM. Surgical factors and rehabilitation have been studied extensively, and it is certain they affect the range

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of motion after TKA (*10,20,23,28*). Currently, pre-operative ROM is widely considered to have the most important influence on the post-operative ROM (*19,21,26*). The ability of TKA designs to accommodate and/or promote full ROM is another important factor that has received less scrutiny. Recently, several fluoroscopic studies of *in vivo* TKA kinematics have suggested methods for improving ROM. In a study of 150 consecutive knee arthroplasties Bellemans *et al* (*6*) found that maintaining a normal posterior condylar offset correlated with greater maximum flexion. They suggested that a prosthesis or femoral component placement providing anatomical posterior condylar offset would promote a larger ROM than a reconstruction decreasing the condylar offset from its anatomic dimension. In a study of 16 different implants, Banks *et al* (*3*) reported that anteroposterior tibiofemoral motions influence the mechanics of weight bearing deep flexion in well-functioning knee arthroplasties. They suggested that a more posterior femoral position on the tibial plateau would enhance the maximum flexion. Bellemans *et al* (*7*) studied the influence of posterior tibial slope on flexion at posterior impingement, and concluded that posterior impingement was delayed by 1.7° of flexion for each additional degree of posterior tibial slope.

Previous implant retrieval studies (*13*) and kinematic studies (*1,2*) showed that PCL-retaining TKA designs exhibit a paradoxical condylar translation. Both condyles show anterior translation with the medial translation much larger than the lateral translation, resulting in a lateral pivot.

These and other findings have provided the basis for a variety of new TKA designs, including the Data Driven Design Knee, or 3D Knee™ (Encore Medical, Austin, TX). The 3D Knee™ is a fixed-bearing cruciate-retaining TKA designed to control AP motion and provide anatomic posterior condylar geometry. It provides a spherical lateral articulation that is fully congruent from extension through 75° flexion and a sagittally curved medial articulation permitting internal/external rotation. This lateral congruency forces the lateral condyle into a central antero-posterior (AP) position in extension, but allows posterior translation in flexion – approximating the function of the anterior cruciate ligament (ACL).

The femoral condyles have a single sagittal radius from extension through 75° flexion that is placed to provide maximum condylar offset late in the flexion arc (fig 1). The tibiofemoral articulation has a high conformity which increases the contact surface, lowers the contact stress and is meant to reduce the probability of wear (*8*).

A variety of activities has been used to study knee flexion kinematics *in vivo* (*4,11,13*). Lunge activities, which are an exaggerated shoe tying position, have been used to study high flexion kinematics (*3,6*). It is not clear this represents the best or most relevant activity for determining high flexion knee kinematics. It can be argued that kneeling is a better activity for exploring knee kinematics with maximum possible flexion (*14,18*), and that a direct comparison of these two postures would prove useful.

The study has two aims : first to determine the kinematics of a new TKA design in highly flexed postures, and second, to determine if kneeling postures provide greater flexion than lunge postures for the study of knee kinematics.

PATIENTS AND METHODS

Patients

The kinematics of twenty knee implants (3D Knee™, Encore Medical, Austin, TX, USA) were studied in sixteen patients (7M, 9F). The criteria for inclusion were good clinical performance, willingness to participate, and a combined Knee Society Knee score (*16*) greater than 180 at least 6-12 months post surgery. All patients gave written informed consent to participate in this Institutional Review Board approved study. Patients averaged 69 (43-84) years, 80 (55-98) kg and had an average Body Mass Index of 28 (20-29) kg/m^2. The prostheses were *in situ* an average of 13 (4-24) months. One knee was examined prior to 6-12 months follow-up because the patient's contralateral knee met the study inclusion criteria. Passive range of motion measured by goniometer averaged 104° (90-125) preoperatively and was 121° (105°-137°) at the time of the study. One knee received manipulation under anaesthesia to improve range of motion after post-operative pain delayed physical therapy.

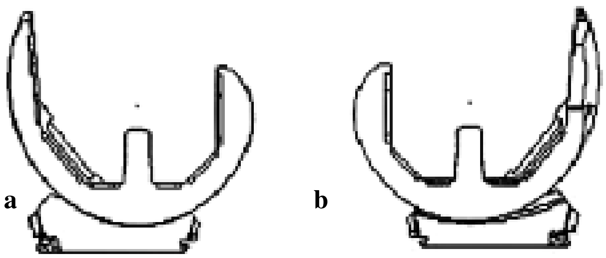

Fig. 1. — Lateral (a) and medial (b) views of the 3D Knee design which provides a spherical lateral articulation that is fully congruent from extension through 75° flexion and a sagittally curved medial articulation permitting endo/exorotation. The femoral condyles have a single sagittal radius from extension through 75° flexion that is placed to provide maximum condylar offset late in the flexion arc.

Fig. 2. — Subjects performed two high flexion activities for the study. a. Kneeling activity. b. Lunge activity.

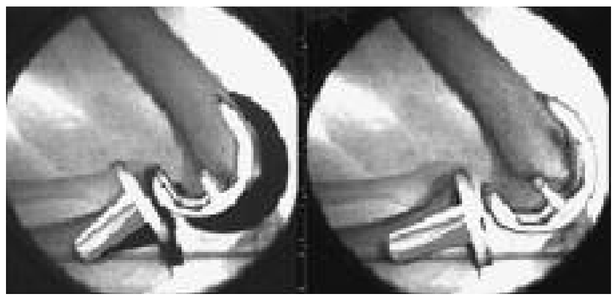

Fig. 3. — Manufacturer supplied implant surface models were projected onto the distortion corrected image and iteratively adjusted to match the x-ray silhouette of the patient's implants.

Surgical procedure

A single surgeon (WAH) performed all surgical procedures using a uniform technique. The proximal tibial plateau was resected parallel to the anatomic surface (*23*). The PCL was fully maintained at its tibial insertion, guarded by an osteotome during the tibial resection. Femoral component external rotation was determined from the epicondyles (*6*) and averaged 3°.

Deep flexion activities

Knee kinematics were determined in subjects during two weight bearing deep flexion activities (fig 2). The subjects placed their foot upon a 30-cm riser and lunged forward with their operated knee to maximum comfortable flexion. The patients also kneeled on a padded chair with their operated knee and flexed to their maximum comfortable flexion. Once the subjects had reached their maximal flexed position, one to three seconds of fluoroscopic images were recorded onto digital videotape. The subjects' postures were not constrained in any way during these activities. An investigator was always available to assist the subjects in case of misbalance by holding their hands or forearms.

Data analysis

Previously reported shape matching techniques were used to determine the three-dimensional position and orientation of the implant components in the digitised fluoroscopy images (*5*). A manufacturer supplied implant surface model was projected onto the distortion corrected image, and its three dimensional pose was iteratively adjusted to match its silhouette with the silhouette of the subject's knee implants (fig 3). Standard errors for this shape matching process are approximately 0.5° to 1.0° for rotations and 0.5 to 1.0 mm for translations in the sagittal plane (*3*). The 3-1-2 Cardan angle convention (*32*) was used to describe joint angles. Condylar translations were determined from the anteroposterior location of the lowest point on each femoral condyle relative to the transverse plane of the tibial baseplate. Femoral anteroposterior location relative to the tibial baseplate was defined as the midpoint between the condylar anteroposterior locations.

Skeletal flexion vs implant flexion

Kinematics determined from shape matching describe the relative pose of the implant components, including the implant flexion angle. In order to describe the anatomic or skeletal flexion angle, it is necessary to

Table I. — Comparison between the 3D Knee™ system during two weightbearing deep flexion activities

Parameter	Lunge Activity	Kneeling Activity
Maximum implant flexion	112° ± 11° (89° to 138°)*	124° ± 11° (103° to 148°)*
Maximum skeletal flexion	120° ± 11° (95° to 147°)*	131° ± 13° (109° to 160°)*
Tibial internal rotation	11° ± 4° (16° to -3°)	10° ± 4° (18° to -3°)
Lateral condyle AP position (mm)	-8 ± 4 (-15 to -1)	-10 ± 4 (-20 to -1)
Medial condyle AP position (mm)	0 ± 4 (-6 to 8)	-2 ± 4 (-10 to 8)

* Indicating a significant difference between lunge and kneeling kinematics in the 3D Knee™ system using a two sided paired t-test, $p < 0.05$.

include the alignment of the implants with respect to the mechanical axes of the tibia and femur. Postoperative lateral x-ray films were used to determine the sagittal alignment of the femoral and tibial components.

Statistics

The paired t-test was used to compare knee flexion, AP-position and tibial rotation during lunge and kneeling activities.

RESULTS

Maximum skeletal flexion during the lunge activity ranged from 95° to 147° with an average of 120° ± 11°. The AP position of the lateral femoral condyle averaged 8 ± 4 mm posterior to the AP midpoint of the tibial insert. The medial femoral condyle AP position averaged 0 ± 4 mm. Tibial internal rotation averaged 11° ± 4°.

Maximum skeletal flexion in kneeling ranged from 109° to 160° with an average of 131° ± 11°, which was significantly higher than during lunge ($p < 0.05$). The AP position of the lateral femoral condyle was -10 ± 4 mm ($p > 0.05$). The AP position of the medial femoral condyle was -2 ± 4 mm ($p > 0.05$). Tibial internal rotation averaged 10° ± 4° ($p > 0.05$).

The implant components averaged 7.3° ± 3.2° extension with respect to the sagittal mechanical axis in standing.

DISCUSSION

High flexion after TKA is a much-desired clinical outcome, especially in cultures where daily activities include praying from the floor or cross-legged sitting (111° to 165°) (*24*). Knee implant design characteristics play an important role in providing high flexion. The current study quantified the kinematics of a new TKA design in highly flexed postures in North American patients. These patients demonstrated average skeletal flexion of 120° in lunge and 131° in kneeling. The kneeling posture produced greater knee flexion and posterior medial condylar translation than the lunge activity. Greater posterior condylar translation with greater flexion is indicative of posterior cruciate ligament function (*22*).

This study characterised flexion kinematics of a knee implant design incorporating two features intended to improve flexion : A highly congruent tibiofemoral articulation that restricted the femur from skidding forward in deep flexion, and a posterior femoral condyle shaped to provide maximum condylar offset late in the flexion arc. Compared to a prior study of 63 knees with 9 different fixed bearing cruciate retaining TKA implants during the lunge activity (*1*), patients with the 3D Knee™ show an average of 5° more flexion ($p = 0.09$) and 3° more internal tibial rotation ($p < 0.05$). This is an imperfect comparison, as patients in the previous study were recruited specifically for superior clinical and functional outcomes, were an average of 26 months post surgery, and had an average 108° preoperative flexion. Randomised, prospective comparisons of different TKA designs are now being undertaken.

Improving pre-operative range of motion is one of the main objectives in TKA surgery. Schurman *et al* (*29,30*) indicated that gaining ROM was mostly achieved by reducing preoperative

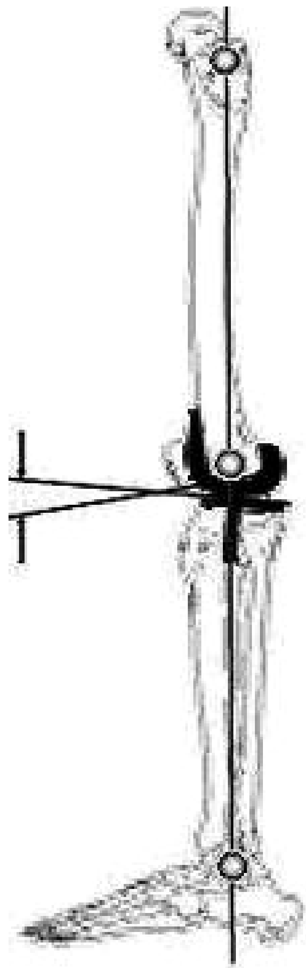

Fig. 4. — Fluoroscopic studies report the flexion angles between the two implant components. These differ from skeletal flexion angles because of anterior bow of the femur and posterior slope of the tibial articular surface. Three-month postoperative films were used to determine implant alignment and were used to calculate true skeletal flexion.

flexion contractures. Considering maximum flexion, Schurman *et al* showed that only patients with poor preoperative flexion gained significant flexion postoperatively, and that patients with good preoperative flexion gained little or even lost flexion postoperatively. In this study we observed that each patient gained an average of 16° maximum flexion postoperatively. This finding is representative of the larger clinical series, wherein the first 100 patients receiving this prosthesis had an average maximum flexion of 108° preoperatively and averaged 123° maximum flexion at 2 years postoperatively.

This study investigated if kneeling provides greater flexion or characteristically different kinematic information compared to the lunge activity. Knees showed an average of 11° more flexion ($p < 0.05$) and 3 mm more posterior femoral translation ($p = 0.11$) during kneeling. Tibial rotation was not significantly different for the two activities. The kneeling activity provides higher flexion angles and therefore may provide more relevant information for assessing the function of knee implants for floor-sitting lifestyles and activities requiring extreme flexion.

Kneeling data previously has been reported for North American patients with a flexion-enhanced fixed-bearing posterior stabilised knee arthroplasty (Scorpio Superflex, Stryker Howmedica Osteonics, Mahwah, NJ,USA) (*2*). To our knowledge, these are the highest average knee flexion results published for North American patients using any prosthesis. These patients showed 130° maximum implant flexion, 13 mm posterior femoral translation, and 4° of internal tibial rotation (*4*). Maximum kneeling implant flexion in the 3D Knee™ group was four degrees less, posterior femoral translation was 7mm less, while tibial rotation was 7 degrees more. These data suggest that high flexion can be achieved using different design strategies, and that the details of the resulting motions (translations and rotations) may differ accordingly. Maximum flexion in posterior stabilised knees benefits from cam and post enforced posterior femoral translation, while cruciate retaining knees rely on restoration of posterior condylar offset and control of tibiofemoral translations by the posterior cruciate ligament and the articular surfaces.

In an MRI-study of 20 healthy Asian subjects, Nakagawa *et al* (*25*) reported full active flexion of 133 ± 9° with 15° ± 9° of internal tibial rotation and maximum passive flexion of 163° with 28° of internal tibial rotation. We observed passive skeletal flexion up to 160° and tibial rotations of 18° in knees with arthroplasty, but average tibial rotations were lower than observed in healthy knees with intact cruciates. With posterior cruciate retaining knee arthroplasty, it appears that tibial rotation is more strongly influenced by the particular activity performed than by intrinsic ligamentous constraints.

TKA design is an important factor in achieving high flexion post-operatively. This study shows that it is possible to achieve good high flexion performance with fixed-bearing cruciate-retaining TKA in North American patients. Maintaining the posterior condylar offset and reducing femoral anterior translation with a sagittally curved tibial surface are design elements that likely contribute to satisfactory flexion performance. It is also shown that kneeling activities provide higher flexion information than lunge activities, and that both might be useful for future tests of deep flexion with TKA.

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