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Kinematic Differences Between Gender Specific and Traditional Knee Implants

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ABSTRACT

In the ongoing debate about gender-specific (GS) vs. traditional knee implants, there is limited information about patella-specific outcomes. GS femoral component features should provide better patellar tracking, but techniques have not existed previously to test this accurately. Using novel computed tomography and radiography imaging protocols, 15 GS knees were compared to 10 traditional knees, for the 6 degrees of freedom of the patellofemoral and tibiofemoral joints throughout the range of motion, plus other geometric measures and quality of life (QOL). Significant differences were found for patellar medial/lateral shift, where the patella was shifted more laterally for the GS femoral component. Neither group demonstrated patellar maltracking. There were no other significant differences in this well-functioning group.

Gender-specific (GS) implants for total knee arthroplasty (TKA) have received considerable attention and controversy recently, yet little attention has been paid to the patellofemoral joint. Recent studies have found lower functional scores, patellar scores and stairs scores in women compared to men [1,2]. Patellar kinematics may also differ in females before and after total knee arthroplasty, with greater lateral tilt compared to males shown during passive intraoperative flexion [3]. Design features of the GS implants, which include a more laterally-oriented femoral groove and a thinner anterior flange (Fig. 1), have the potential to improve patellar tracking.

The design differences between GS and traditional implants are intended to reflect anatomical differences between male and female knees. Female knees on average have narrower mediolateral dimensions [4,5], a more trapezoidal distal femur [6], and the patellofemoral groove is angled more externally relative to the femoral epicondylar line [5] compared to male knees. GS implants have therefore been designed with a reduced mediolateral to anteroposterior (ML/AP) aspect ratio, a thinner anterior flange and a larger trochlear groove angle compared to their traditional knee component (Fig. 1) [7].

One of the main goals of fitting the anatomy better is to require fewer intraoperative adjustments. Adjustments include either downsizing or upsizing the component. Downsizing the component requires a change to the AP positioning, affecting the flexion and extension gaps, which can result in an unstable or stiff knee; it also risks leaving more bone exposed. Upsizing the component risks overstuffing the joint and having the femoral component overhang medially or laterally. Reducing the ML/AP ratio of the femoral component makes it theoretically possible to reduce mediolateral overhang in women [8], although this may or may not be achieved in practice [9,10]. By having a thinner anterior flange the risk of overstuffing the knee is reduced. Overstuffing the knee can reduce the range of motion (ROM) and increase the likelihood of anterior knee pain [11]. A larger trochlear groove angle accommodates the larger quadriceps (Q)-angle of females, which could thereby provide better patellar tracking [7].

Studies comparing the clinical outcome of GS implants to traditional implants have not found an improved outcome among women with GS implants, based on traditional scores [12,13]. However, there are several factors that traditional scores do not include, especially anterior knee pain (AKP). Factors beyond the traditional measures should be investigated further, especially given that approximately 18% of patients are not satisfied with their TKA [14].

One of the factors that affects AKP is patellar tracking, where patellar maltracking has been defined as shift>5 mm or tilt>5° [15]. Other factors that affect patellar tracking include: implant type [16],

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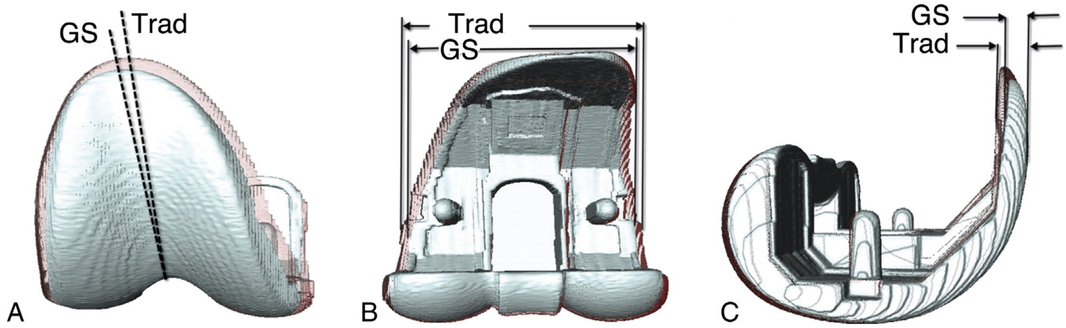

Fig. 1. The GS femoral component (white) overlaid onto a traditional component (red): (A) the GS component has a more lateral femoral groove compared to the traditional component; (B) the GS component has a narrower mediolateral/anteroposterior ratio; and (C) the GS component has a thinner anterior flange.

positioning of the components [17], and surgical technique [17], all factors relating to the articular geometry of the knee.

To our knowledge, no other study has been performed that evaluates what effect GS knees have on patellofemoral (PF) or tibiofemoral (TF) joint kinematics. The purpose of this study, therefore, was to determine whether PF kinematics, TF kinematics or quality of life differs between patients with GS and traditional implants. The hypothesis was that the kinematics would differ due to the more lateralized groove and thinner anterior flange. Differences were primarily expected in patellar kinematics in early flexion since this is where the two designs differ.

Materials and Methods

Subjects

We imaged and analyzed 24 TKA female subjects, including one bilateral, resulting in a total of 15 GS knees and 10 traditional knees. The traditional group was operated on within a year before the GS knees were introduced. Both the GS and traditional group had a minimum of 2 years follow-up prior to testing, averaging 3.6 years for the GS group and 4.5 years for the traditional group. Since the two surgeons involved in the study currently use GS components on almost all of their female patients due to the better fit (judged intraoperatively for each case), it can be assumed that the subjects in the traditional group would have received a GS implant if it had been available. All implants belonged to the NexGen Legacy Posterior Stabilized knee prosthesis system (NexGen LPS; Zimmer Inc., Warsaw, IN, USA), using either Gender Solutions or traditional components. All subjects had a resurfaced patellar component. Age and BMI were not significantly different between the two groups ($P>0.44$; Table 1). The patients were operated on by two experienced, fellowship-trained surgeons, one using a medial parapatellar approach (9 GS, 7 Trad), the other using a quad-sparing minimally-invasive approach (6 GS, 3 Trad); otherwise, the operating techniques were similar. There were no significant differences in age or BMI between the subjects for each surgeon ($P>0.19$). Our institutional review board approved the study, and written informed consent was obtained from all patients.

Table 1
Age and BMI for GS and Traditional Groups.

	Age (Years)	BMI (kg/m^2)
Trad mean ± SD	67.7 ± 9.4	32.4 ± 6.3
GS mean ± SD	65.3 ± 10.7	30.2 ± 7.6
P value	0.58	0.44

Imaging Protocols

Evaluating patellar tracking postoperatively is difficult because the patellar component is blocked by the metal femoral component from most directions when imaged with radiography or fluoroscopy and is usually obscured by metal artifact when using computed tomography (CT) or magnetic resonance imaging (MRI). Our research group has developed *in vivo* imaging protocols that make it possible, for the first time, to measure the full six degrees of freedom (DOF) of PF as well as TF kinematics accurately after arthroplasty, throughout the range of motion, using CT [18] and radiography [19]. To compare and eliminate other factors that may influence patellar tracking, we also measured component positioning relative to the bone, joint line changes, patellar height, and hip-knee-ankle (HKA) angle.

CT – Protocol

The subject's hip, knee and ankle were imaged with a Siemens SOMATOM 64-slice CT machine (Siemens; Berlin, Germany) with the knee at 0° flexion. In order to have the patient partially load-bear the knee while lying down on the scanner bed, they pressed their heel against a pivoting plate on a custom knee rig to resist a 9 kg weight (Fig. 2).This load level was chosen to provide resistance while still allowing the subject to hold the position stationary and without pain. Adjusting the weight according to bodyweight would have been too demanding for some subjects.

Fig. 2. CT set up. A custom knee rig was designed to have the subjects partially loading their knee while the CT scan is taken of their knee. The platform onto which the subject pushes with their heel is attached to a weight by a series of pulleys. The weight is used to apply force to the patient's heel and simulate partial loadbearing of their leg. The knee rig can be adjusted to fit different lengths of legs and the leg platform can be tilted to get the patella out of the metal artifact band from the femoral component.

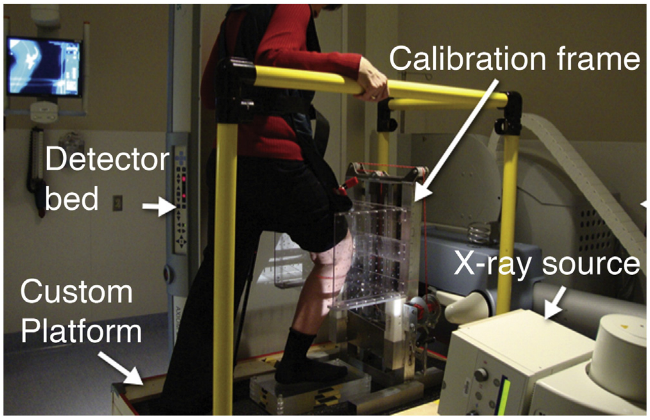

Fig. 3. Radiographic sagittal set up showing the subject standing on a platform weightbearing on their leg; the knee is bent to different flexion angles by using different step heights. A calibration frame surrounds the knee in order to determine the location of the knee in space. The calibration frame can be moved up and down depending on the location of the knee. The detector bed is rotated vertically with the X-ray source taking sagittal images.

Radiography – Protocol

Sagittal View. Static radiographic images were taken with a Siemens AXIOM Luminos dRF flat-bed fluoroscopy unit (Siemens; Berlin, Germany) at 8 different knee flexion angles: 0°, 15°, 30°, 45°, 60°, 75°, 90° and at max flexion, measured using a goniometer. All images were taken with the subject fully weightbearing the knee (Fig. 3). For each knee flexion angle a set of two images was taken, one with the X-ray source at horizontal and one with the X-ray source 10° below horizontal. Having two images from two different angles provided out-of-plane information. Around the subject's knee was a calibration frame, which made it possible to calibrate the X-ray images using a custom Matlab program (R2011a, Mathworks; Natick MA, USA).

In addition to measuring patellofemoral kinematics relative to the femoral coordinate system, we measured the medial-lateral shift of the patella within the femoral groove. Shift of the patellar component apex was computed relative to the deepest point within the femoral groove. This was measured on the 3D reconstructions from the 2D sagittal images for 45° and 90° knee flexion and from the 0° CT data.

Skyline View. The X-ray source and the detector bed were rotated 90° to take images from the skyline view (Fig. 4). This view helped to analyze how well the patella was tracking in the femoral groove and made it easier to detect patellar tilt and shift, which are potential contributors to AKP. The subjects were imaged at 4 flexion angles: 45°, 60°, 75° and 90°.

Image Analysis

Three-dimensional (3D) models were created of the implant components by reverse engineering a high resolution CT scan of the components using image analysis software (Amira, VSG; France). Coordinate systems were assigned to the models using features on each prosthesis component (Fig. 5).

The calibrated 2D images and the 3D implant models were imported into the open-source software, JointTrack Bi-plane (Dr. Scott Banks, University of Florida, USA; sourceforge.net/projects/jointtrack/ [20]). Using JointTrack Bi-plane the 3D models were matched separately to the set of two 2D images. The matching was performed manually for each knee flexion angle (Fig. 6), as this improved the accuracy of the fit compared to automated fitting. To address slight movement between the two images, we first matched to one image, using the second image as a reference, then matched to the second image using the first as a reference and then averaged the results. This approach had better repeatability and better out-of-plane accuracy than matching to a single image. Using a custom Matlab program the 6 DOF were computed for the patellar component and the tibial component relative to the femoral component. Kinematics were compared at the nominal flexion angles since small differences in the true angles would not have affected the results. Full details of the method are available elsewhere [19]. Validation in comparison to computed tomography (CT) imaging showed accuracy within 0.4 mm and 0.9º for the patellofemoral joint and within 0.9 mm and 0.4º for the tibiofemoral joint [19].

Geometry Analysis

To ensure comparable groups, we measured the following factors that can contribute to patellar misalignment: femoral component rotation, measured according to the surgical transepicondylar axis [21]; tibial component rotation [22], measured according to the medial third of the tibial tubercle; joint line height changes [23]; patellar bone thickness; HKA angle, measured according to the mechanical axis [24]; and patellar height, using the Insall-Salvati (IS) ratio [25].

Quality of Life

In addition to the kinematic data, we collected quality of life (QOL) data to determine whether different kinematics and component design would affect the subjects' QOL. The QOL data collected were: Hospital for Special Surgery (HSS) Patella Score [26], Western Ontario and McMaster Universities Osteoarthritis Index (WOMAC) score [27], Oxford-12 score [28], SF-12 quality of life score [29] and the Knee Society Score [30]. The QOL data provided the possibility to determine whether abnormal kinematics and implant design affect AKP and the patient's QOL.

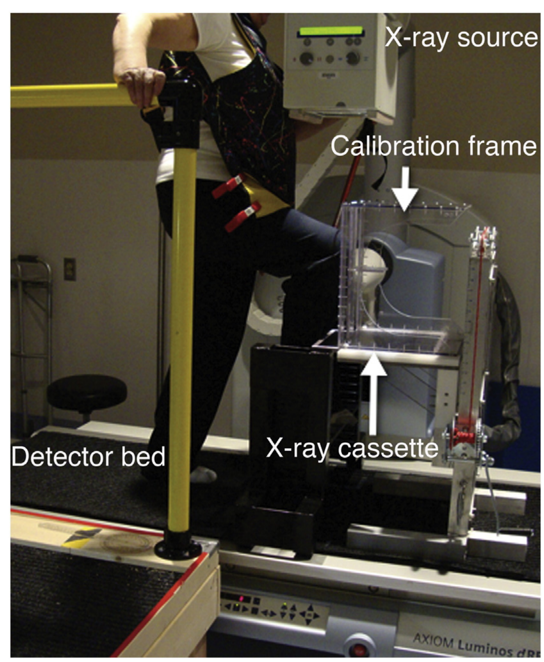

Fig. 4. Radiographic skyline set up shows the subject standing on the detector bed weightbearing on their leg. The knee can be bent to different flexion angles using different step heights. A calibration frame is in front of their knee in order to detect the location of the knee in space. The calibration frame can be moved up and down depending on the location of the knee. The detector bed is rotated horizontally with the X-ray source above the knee to take skyline images. An X-ray cassette is located underneath the calibration frame to get better quality images.

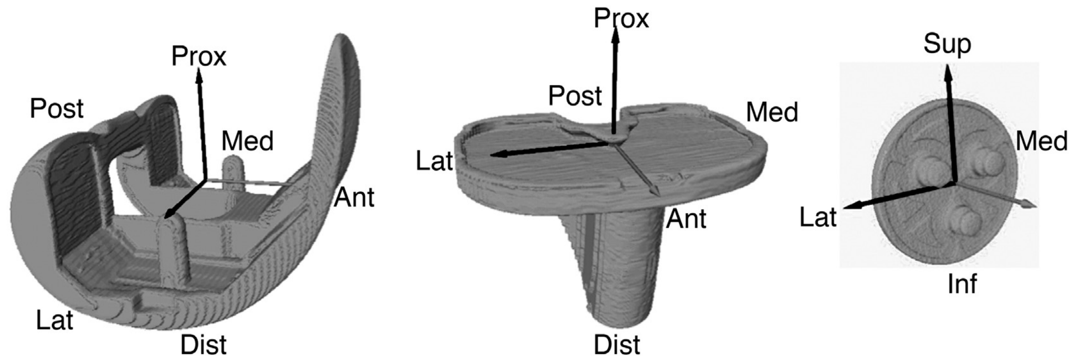

Fig. 5. Postoperative implant coordinate systems.

Statistical Analysis

We compared the variables of the two groups, GS vs. traditional, using Student's two-tailed t-tests. Statistical significance was defined as P values less than 0.05.

Results

We found a significant difference between GS and traditional femoral components for the PF kinematics in early flexion relative to the femoral component ($P<0.001$ at 0º and $P=0.04$ at 15º; Fig. 7) and at 45º for shift within the femoral groove ($P=0.01$; Table 2), confirming our original hypothesis. There were no significant differences between the subjects' QOL (Table 3), nor in their tibiofemoral kinematics (Fig. 8). The only significant difference for the geometry measures was for patellar height where the IS ratio for the traditional group was 1.1 ± 0.1 compared to 1.0 ± 0.2 for the GS group (Table 4).There were no significant differences between the surgeons' groups. Therefore, subject results for the two surgeons were pooled. All subjects had good QOL and function and were satisfied with their TKA.

The patella was more lateral for the GS femoral components relative to the center of the femoral component (Fig. 7): at 0° knee flexion the patella was shifted by 5.3 ± 1.6 mm laterally for the GS component compared to 3.9 ± 1.0 mm for the traditional component; at 15° knee flexion the patella was shifted 3.2 ± 0.9 mm laterally for the GS component compared to 2.3 ± 1.2 mm for the traditional component. There were no noticeable differences for the one bilateral subject.

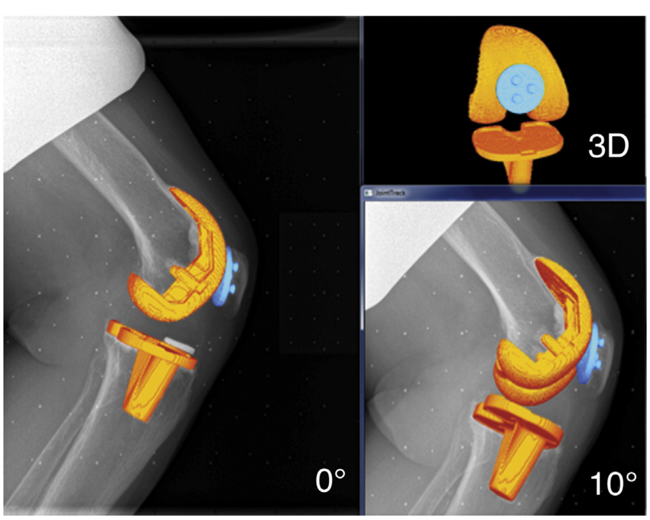

Fig. 6. Postoperative images from JointTrack Biplane. The three windows show the sagittal X-ray images where the X-ray source is at 0° and 10° as well as a 3D view of the components.

The patella was also more lateral for the GS femoral components relative to the deepest point of the femoral groove (Fig. 9, Table 2). On average the patella at 45° was shifted by 1.4 ± 2.1 mm laterally for the GS group while it was shifted by 0.8 ± 2.1 mm medially for the traditional group. For 0° and 90° knee flexion there was not a significant difference for the patellar shift but on average the patella was shifted more laterally for the GS group versus the traditional.

Discussion

This study compared GS femoral implants to traditional implants by determining the PF and TF kinematics throughout the range of motion using a novel *in vivo* protocol. We found that GS implants affected the patellar shift in relation to the origin of the femoral component in early flexion and the shift within the femoral groove at mid-flexion, with a trend in both early and late flexion. The GS femoral component is designed with a more lateralized femoral groove, which explains why the patella tracks more laterally in relation to the origin of the femoral component in early flexion; in later flexion, the two groove geometries coincide in design, but may differ based on component positioning. The average patellar shift in the femoral groove was within 1.5 mm for both groups. Since patellar maltracking is defined as a 5 mm shift out of the groove [15] both groups had good patellar tracking; therefore we cannot draw the conclusion that either component provides better patellar tracking.

For patellar tilt a previous study also found no significant difference in postoperative tilt angle between a traditional and GS group with the same prosthesis system, based on radiographic measurements (averaging $7.7°\pm4.4°$ vs. $6.0°\pm3.8°$, respectively) [13]. Similar to our study there is a large standard deviation. In our study we found the tilt to be $1°\pm5°$ for the traditional group and $1°\pm4°$ for the GS group throughout the range of motion. Our smaller values are likely because our subjects were weightbearing, which has been shown to be a better judge of relevant tilt, and correlates better with clinical symptoms [31].

We performed the geometry measurements to rule out geometric differences affecting the patellar tracking or being a factor influencing the subject's kinematics. Femoral component rotation has been reported to affect patellar tracking, where previous studies have found that external rotation of up to 5° provides good tracking [21]. For the GS group the average external rotation was 3.2° compared to 4.0° for the traditional group. Both surgeons in the study favored external rotation of the femoral component. For the traditional group the patella tracked on average more on the medial side of the femoral groove (Table 2), which correlates with a more externally rotated femoral component. Therefore, we cannot draw the conclusion that the differences in shift of the patella within the femoral groove are related to the different femoral component designs.

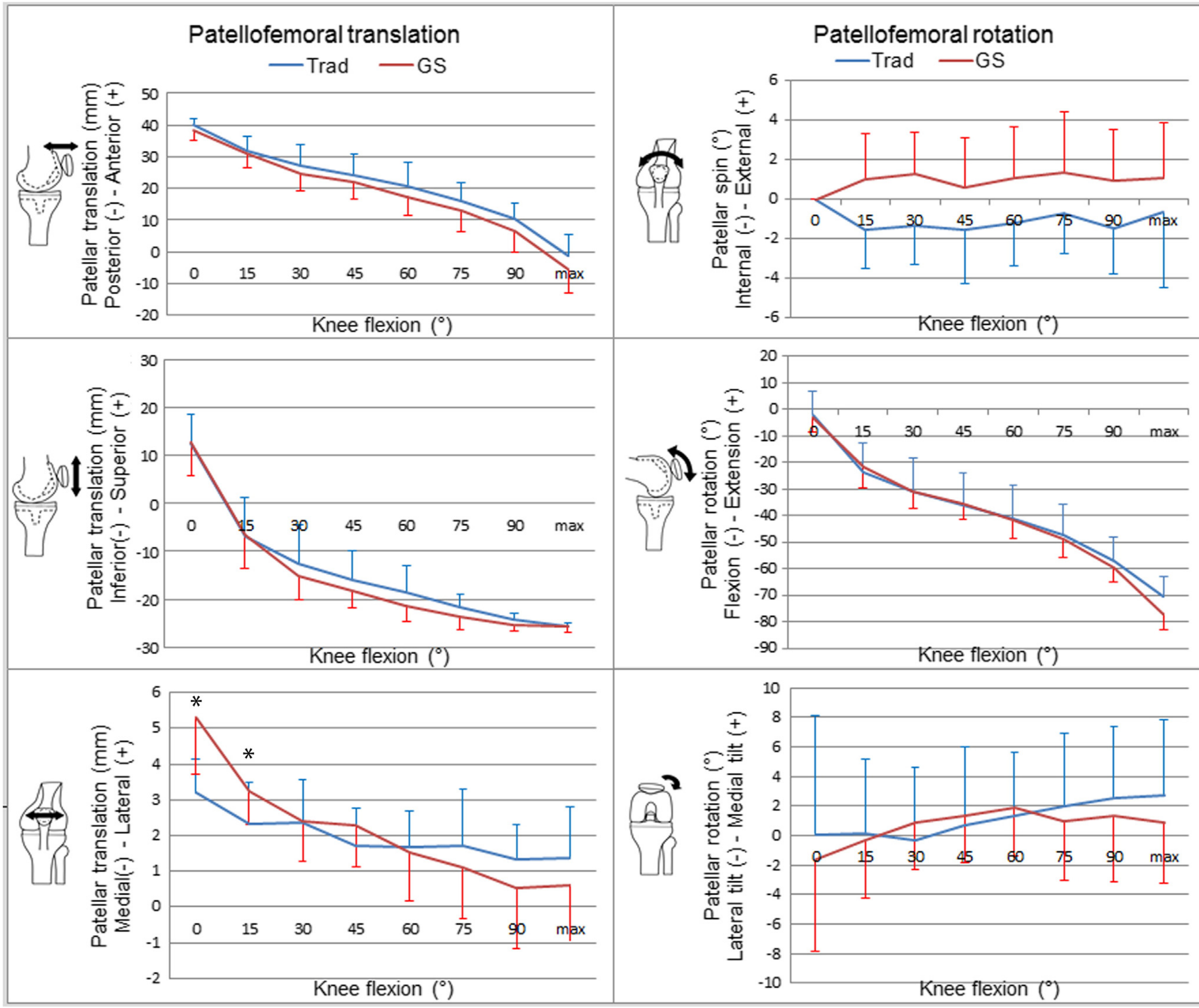

Fig. 7. Average patellofemoral kinematics with standard deviations. Icons next to the graphs show the translations and rotations presented in each graph. Subjects with GS femoral implants are shown with a red line and subjects with traditional implants are shown with a blue line. Standard deviation (SD) is shown with a unidirectional error bar for improved visuals; the true error bars are ±SD. Note that different scales are used for each graph. Asterisks on the PF mediolateral translation graph show statistical significance.

Tibial component rotation has also been found to correlate with patellar complications such as AKP [32]. For the GS group the tibial component rotation ranged from 0.5° external rotation to 21.0° internal rotation (mean: 9.7º); for the traditional group it ranged from 2.5° external rotation to 11.8° internal rotation (mean 6.7º). Internal tibial component rotation in the range of 0°–10°has been found to be clinically acceptable [33]. There were no clear trends between tibial component rotation and patellar tracking, despite the wide range of variation in tibial component rotation. This is in agreement with an *ex vivo* study using the same implant design that showed no consistent effect of tibial rotation on patellar tracking [17]. Furthermore, there was no evidence that patient satisfaction or quality of life was affected by tibial component rotation.

Joint line elevation change beyond 5 mm has been related to patellar complications [34]. Failure to restore the joint line affects the superior/inferior location of the patella relative to the femur. An abnormally high patella is referred to as patella alta where the IS ratio measured is above 1.2 and an abnormally low patella is referred to as patella baja with an IS ratio below 0.8 [25]. For both the GS group and

Table 2
Patellar Shift Relative to the Deepest Point of the Femoral Groove in the GS and Traditional Femoral Components.

	Patellar Shift in Groove 0° Flex (mm)	Patellar Shift in Groove 45° Flex (mm)	Patellar Shift in Groove 90° Flex (mm)
Trad mean ± SD	1.19 ± 2.29	0.82 ± 2.05	0.50 ± 2.09
GS mean ± SD	−0.41 ± 2.46	−1.43 ± 2.09	−0.84 ± 1.72
P value	0.12	0.01	0.10

The table shows the measurements for 3 different flexion angles 0°, 45° and 90°. Positive numbers are medial shift, negative numbers are lateral shift.

Table 3
GS and Traditional QOL Scores for Each Group, With SD and *P* values. SF-12 Abbreviations Are: Physical Component Summary (PCS) and Mental Component Summary (MCS).

	HSS Patella Score	KSS Knee Score	WOMAC Score	Oxford Score	SF-12 Score PCS	SF-12 Score MCS
Trad mean ± SD	87.0 ± 11.4	82.9 ± 14.3	16.1 ± 14.8	38.7 ± 8.9	42.0 ± 12.2	53.7 ± 11.9
GS mean ± SD	88.0 ± 11.9	82.1 ± 12.2	9.3 ± 9.5	41.3 ± 5.1	45.9 ± 11.0	54.4 ± 7.2
P value	0.84	0.89	0.17	0.35	0.41	0.86

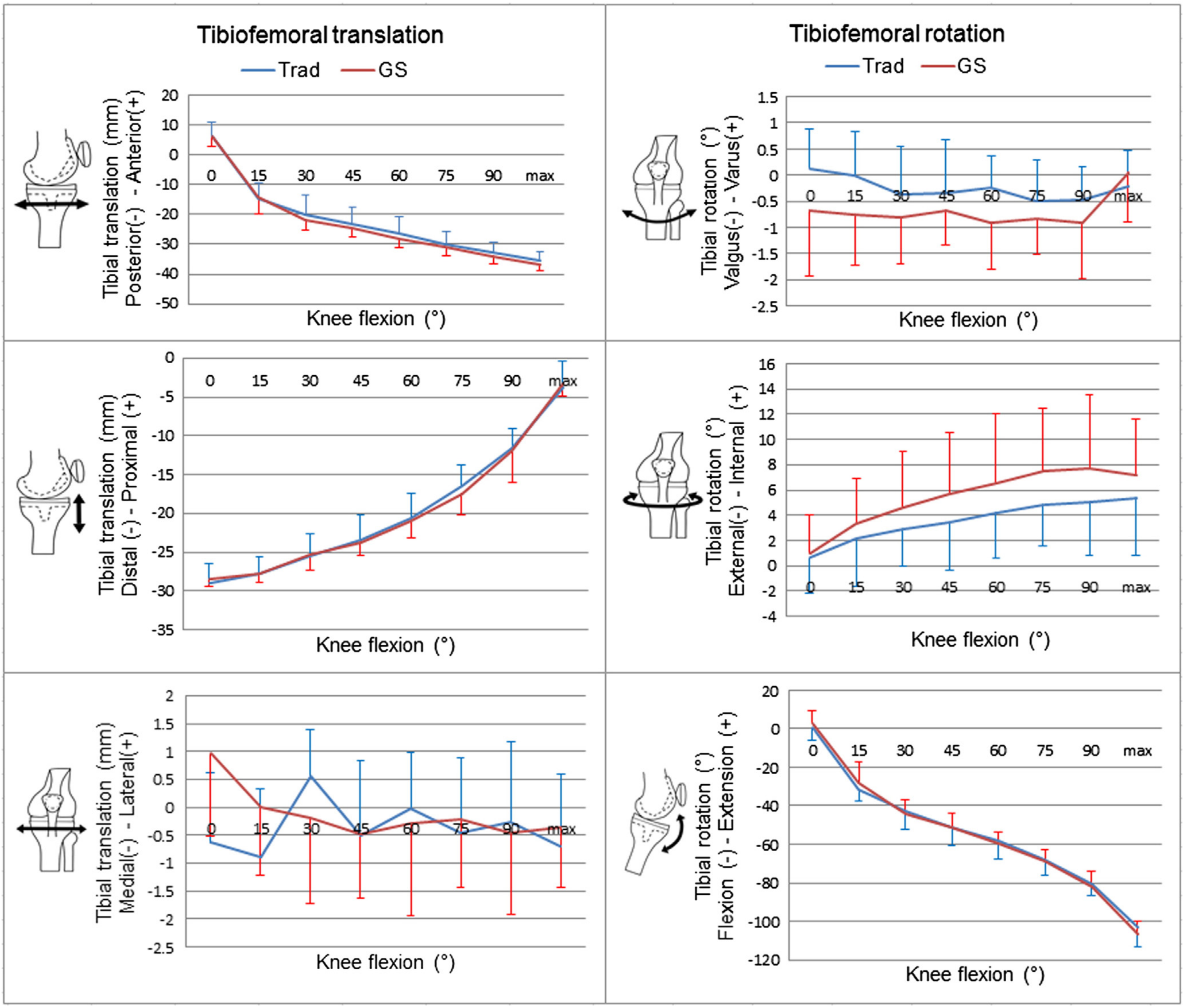

Fig. 8. Average tibiofemoral kinematics with SD. Icons next to the graphs show the translations and rotations presented on each graph. Subjects with GS femoral implants are shown with a red line and subjects with traditional implants are shown with a blue line. Standard deviation (SD) is shown with a unidirectional error bar for improved visuals; the true errors bars are ±SD. Note that different scales are used for the graphs; the error bars for mediolateral tibial translation, for example, span only a few degrees.

the traditional group the average IS ratio was within 0.8–1.2 and the joint line changes were within 5 mm.

HKA angle is used to determine if one side of the knee is being overloaded due to valgus (positive HKA angle) or varus (negative HKA angle) malalignment. The normal range for the HKA angle has been found to be around 1.0 ± 2.9° varus [35]. Average HKA angle for the GS group was 1.2 ± 3.6° valgus and 0.7 ± 3.3° varus for the traditional group. There are large variations in "normal" HKA alignment [36] and both groups can be considered within the normal range.

Patellar thickness can also affect the PF kinematics. If the patellar resection leaves the patella too thick it can result in an overstuffed knee, which can limit the range of motion. However, if the patella is too thin (<12 mm) then the risk of patellar fracture is greater [11]. Mean patellar bone thickness for the GS group was 14.4 mm and 14.5 mm for the traditional group.

Both the GS group and the traditional group were in the upper range of the QOL scores meaning that the subjects were in good physical and mental health and were not experiencing any severe patellar or knee problems (Table 3). There were no significant differences in QOL between the two groups.

When fitting traditional femoral components on female femurs intraoperative adjustments normally need to be made, according to

Table 4
GS and Traditional Average Geometry Measurements for Each Group, With SD and *P* Values.

	ROM (°)	Tibial Rotation (°)	Femoral Rotation (°)	HKA (°)	Patellar Thickness (mm)	Patellar Height	Joint Line Change (mm)
Trad Mean	109 ± 11	6.3 ± 4.6	−4.0 ± 1.6	−0.7 ± 3.3	14.4 ± 1.7	1.1 ± 0.1	−0.2 ± 1.3
GS Mean	115 ± 10	9.7 ± 5.9	−3.2 ± 3.3	1.2 ± 3.6	14.5 ± 1.2	1.0 ± 0.2	0.2 ± 2.0
P value	0.19	0.15	0.48	0.19	0.92	0.02	0.60

Internal component rotation is shown with a positive sign, external rotation with a negative sign. HKA angle (valgus alignment: positive, varus alignment: negative). Patellar height is the Insall-Salvati ratio (lowered joint line: positive, raised joint line: negative).

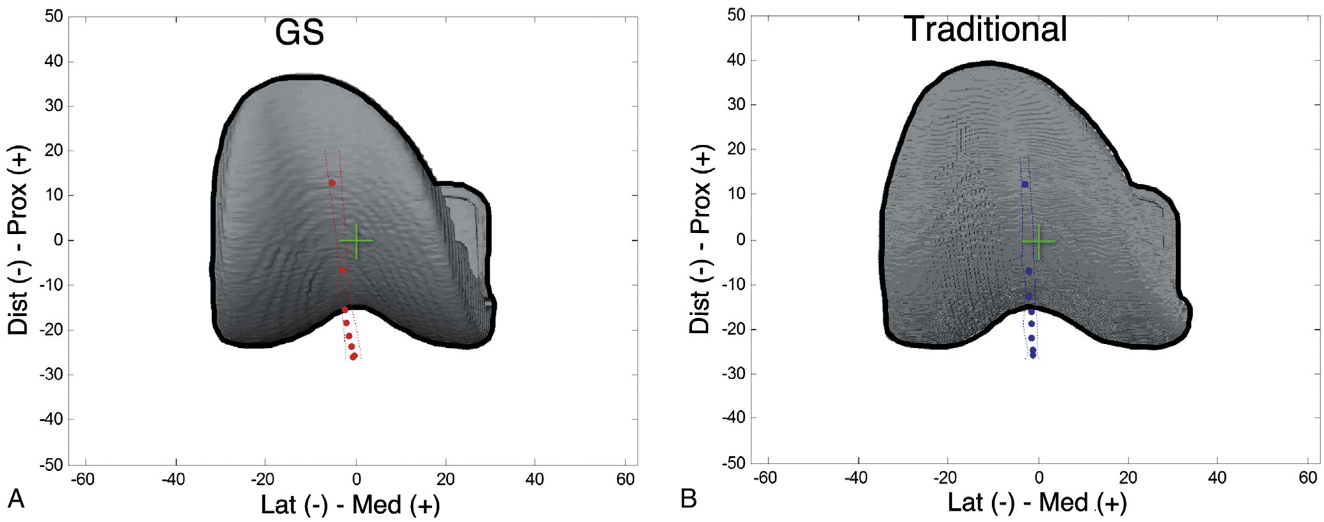

Fig. 9. Patellar shift relative to the deepest point of the femoral groove. Figures show the patellar prosthesis shift relative to the femoral groove, overlaid onto a median size femoral component. The green cross is the origin of the femoral component. The red and blue dots show the average tracking of the patella and the red and blue dashed lines show the SD. (A) GS component. (B) Traditional component.

the experience of the two surgeons participating in the study. These adjustments include: lateralizing the component since it is not built into the traditional component as it is for the GS component; downsizing the component if the femur is between sizes, which can result in a potential notch anteriorly or increased flexion gaps posteriorly, making the implant less stable in flexion; or cutting the patella thinner as the anterior flange is thicker for the traditional component compared to the GS components.

One limitation of the study was the small sample size. There were large variations within the groups, resulting in insignificant differences between the groups. Nevertheless, we do not expect that a larger sample size would reveal substantially different findings in a well-functioning population similar to ours. Furthermore, our protocol was sufficiently sensitive to detect the difference in patellar tracking between the two groups, showing that the design did have an effect. There was some selection bias in terms of healthier subjects participating in the study since subjects with a good mental state, good mobility and good strength were more likely to participate in the study. It would be valuable to study subjects who are experiencing patellar maltracking, pain or reduced range of motion to determine whether a GS component could be of benefit to these patients.

In conclusion, with our newly developed protocols it became possible to evaluate the PF kinematics postoperatively, which revealed differences in the patellar tracking between the GS and traditional femoral implants. Despite large variations in kinematics, the impact of implant design could be seen, even in this well-performing group. There were no significant differences between the groups in terms of their function and QOL, which were both good. The surgeons involved in the study will continue to use the GS femoral implants since they find it easier to fit the GS components for female knees compared to the traditional components.

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