The Effect of Geometric Variations in Posterior-stabilized Knee Designs on Motion Characteristics Measured in a Knee Loading Machine

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Abstract

Background In different posterior-stabilized (PS) total knees, there are considerable variations in condylar surface radii and cam-post geometry. To what extent these variations affect kinematics is not known. Furthermore, there are no clearly defined ideal kinematics for a total knee.

Questions/purposes The purposes of this study were to determine (1) what the kinematic differences are caused by geometrical variations between PS total knee designs in use today; and (2) what design characteristics will produce kinematics that closely resemble that of the normal anatomic knee.

Methods Four current PS designs with different geometries and one experimental asymmetric PS design, with a relatively conforming medial side, were tested in a purpose-built machine. The machine applied combinations of compressive, shear, and torque forces at a sequence of

flexion angles to represent a range of everyday activities, consistent with the ASTM standard test for measuring constraint. The femorotibial contact points, the neutral path of motion, and the AP and internal-external laxities were used as the kinematic indicators.

Results The PS designs showed major differences in motion characteristics among themselves and with motion data from anatomic knees determined in a previous study. Abnormalities in the current designs included symmetric mediolateral motion, susceptibility to excessive AP medial laxity, and reduced laxity in high flexion. The asymmetric-guided motion design alleviated some but not all of the abnormalities.

Conclusions Current PS designs showed kinematic abnormalities to a greater or lesser extent. An asymmetric design may provide a path to achieving a closer match to anatomic kinematics.

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Clinical Relevance One criterion for the evaluation of PS total knees is how closely the kinematics of the prosthesis resemble that of the anatomic knee, because this is likely to affect the quality of function.

Introduction

The two major design types of TKA used today are cruciate-retaining in which the anterior cruciate ligament is resected but the posterior cruciate ligament is preserved and posterior-stabilized (PS) in which both of the cruciates are resected but the function of the posterior cruciate ligament is substituted by elements of implant design. In the PS type, the dishing of the tibial bearing surfaces provides some AP and rotational stability throughout the flexion range, whereas the intercondylar cam-post mechanism engages at approximately 60° to 90° of flexion causing posterior displacement of the femur on the tibia while preventing anterior femoral displacement. Although the PS with an intercondylar cam-post is treated as a generic style of TKA, there are numerous such designs available, which can vary considerably both in the frontal and sagittal radii of the bearing surfaces and in the configuration of the cam-post mechanism. Consequently, for a given set of external forces in function, the neutral path of motion (the motion when only an axial compressive force is acting across the knee) and the AP and rotational laxities measured relative to the neutral path will vary such that it could affect the in vivo kinematics and function [14].

The overall goals of this project were to determine the magnitude of the kinematic differences between different PS designs and to determine what design characteristics would more closely reproduce the kinematics of the anatomic knee. The project was restricted to in vitro evaluation so that the methodology would be applicable at the design stage of a new TKA concept. Several different approaches to in vitro kinematic evaluation of TKA designs have been developed, which could be applied to the design process. These approaches have included the use of Oxford-style knee rigs or robots [11, 15, 25, 26, 33]; loading rigs specifically designed for measuring laxity in line with the ASTM standard on constraint [1, 10, 12, 20, 23]; knee-simulating machines [3, 9]; and computer models [19, 20]. For this study, we developed a desktop knee machine in which combinations of forces and moments were applied to the test knee at a range of flexion angles to represent a spectrum of everyday activities, consistent with the ASTM standard methodology for constraint measurement [1]. Using this approach we were able to compare the motion characteristics of current PS designs between themselves and with the anatomic knee.

We sought (1) to determine whether observed differences in motion parameters (including femorotibial contact

points, neutral path of motion, and laxities about the neutral path) among different PS designs was the result of their geometric differences; and (2) to identify the design characteristics associated with motion parameters that better approximate anatomic motion.

Materials and Methods

The desktop knee machine was constructed according to a layout with defined constraints (Fig. 1). The importance of the constraints has been analyzed in relation to preventing restraint in AP and rotation tests [20]. The tibial component was fixed in a block at a posterior slope angle of 5°. The axial compressive force was applied vertically upward at the center. The component was free to align with the femur in varus-valgus and mediolateral. The femoral mounting block had side axles aligned with the centers of the distal-posterior condylar arcs, the circular axis [5]. The block and axles were connected to a housing (not shown), which was free to rotate about a vertical axis and displace AP. The femoral component was set at the required flexion angle within the housing using a stepper-motor. AP shear forces and axial torques were applied to the femoral housing using double-acting air cylinders controlled by three-way solenoid valves. Data for selecting the range and combinations of the test forces were obtained from instrumented total knees [4, 13]. On applying the forces and torques, the femoral component displaced and rotated on the tibial

Fig. 1 This figure shows a schematic of the desktop knee machine for applying combinations of compressive, shear, and torque forces across the knee at a range of flexion angles with respect to tibial and femoral axes. The components were constrained (C), unconstrained (U), or set (S) at the required angles of tibial slope and femoral flexion.

component. Restraint was provided by the TKA itself as well as by springs that simulated the soft tissues [8, 9]. The degrees of freedom were provided by rolling element bearings with very low friction. The testing parameters were as follows: femoral flexion angles 0°, 15°, 30°, 60°, 90°, and 120°; compressive force 1000 N; AP shear force 200 N; internal-external torque 5 N-meter; the soft tissue representation for AP was ± 2.5 mm no restraint, then 9.13 N/mm restraint; and the soft tissue restraint for torque was $\pm 3^\circ$ no restraint, then 0.13 Nm/degree restraint. For the metal-plastic TKAs, distilled water was used as the lubricant. For the guided motion design, made from a plastic resin, a fluoro-ether lubricant was used (Krytox; DuPont, Bellevue, WA, USA). The average static and dynamic friction coefficients for metal-polyethylene lubricated with distilled water were 0.063 and 0.062. For the resin material lubricated with Krytox grease, the values were 0.076 and 0.054. Hence, the effects of friction on the kinematics would be similar for the two material combinations.

The rationale for the test itself was based on the ASTM standard on quantifying the constraint in a total knee and on identifying the geometric parameters influencing the motion [1, 12, 20]. The test describes the location of the neutral position and the extremities of laxity on applying shear and torque forces. The test is intended to provide comparison between total knees and to describe the behavior at the extremes of motion, which will be encountered in vivo. The test has its foundations in numerous biomechanical studies in which laxity and stability of anatomic knees and total knees have been measured, whereas the mechanics of the machine in this study were based on previous machines in other laboratories as well as our own [9, 10, 12, 18, 20, 25, 27, 29, 31].

Before testing each TKA in the desktop knee machine, three 1-mm conical holes were machined into the femoral and tibial components to act as fiducial points for spatial location. The TKA was first positioned at 0° flexion and the compression force was applied. The six fiducial points were digitized using a Microscribe G2LX (Solution Technologies Inc, Oella, MD, USA) interfacing with Rhinoceros 4.0 (McNeel, Seattle, WA, USA) to an accuracy of 0.2 mm. The anterior shear force was applied and the digitizing repeated followed by the posterior shear force, internal torque, and external torque. This sequence was then repeated for all of the flexion angles. Reproducibly was tested by repeated measurement of the NexGen Legacy design, and also the guided motion design, showing insignificant variations in output displacements.

At the end of the tests, the components were clamped and multiple points were digitized on the bearing surfaces, including the cam and post, together with the fiducial points. From the surface point clouds, three-dimensional stereolithography meshes were created in Rapidform XOR3 software (Inus Technology, Lakewood, CO, USA). From these models, the radii of the femoral and tibial bearing

surfaces in the frontal and sagittal planes were determined. To determine the contact points, the femoral surface was located on the tibial surface for each test condition and the points of closest approach were determined. To estimate actual contact areas for visualization purposes, a finite element analysis was carried out using ANSYS 13.0 (Canonsburg, PA, USA). An elastic-plastic model was used for polyethylene with a modulus of 0.83 kPa and a yield strength of 25 kPa; the coefficient of friction was 0.04. Contact patch dimensions were calculated for combinations of frontal and sagittal radii of the femoral and tibial components at 0° and 45° of flexion under an axial load of 1000 N.

The TKAs were selected to provide a range of geometries and constraints. A design of relatively low constraint was the Deluxe (Beijing Montagne; Zimmer Inc, Warsaw, IN, USA). Three other designs: The NexGen Legacy (Zimmer Inc), the Genesis II (Smith & Nephew, Memphis, TN, USA), and the Hermes Hifit (Ceraver, Roissy, Cedex, France), have been widely used for many years. The radii and bearing spacing (Fig. 2) were measured from the

Fig. 2 This shows the geometric parameters of the bearing surfaces of a typical TKA in the frontal and sagittal planes. D = dwell points (lowest points on the tibial surface); BS = bearing spacing; R = anterior femoral radius; RDF = distal femoral radius; RPF = distal-posterior femoral radius; TA = transition angle between RDF and RPF; ROF = outer femoral radius; RIF = inner femoral radius; RAT = anterior tibial radius; RPT = posterior tibial radius; ROT = outer tibial radius; RIT = inner tibial radius.

Table 1. Dimensional parameters of the test knees

	Radius (mm)	NexGen Legacy	BM Deluxe	Hermes Hifit	Genesis II	Guided motion	
						Medial	Lateral
Frontal inner	R	38.8	69.1	25.5	25.3	41	
	RIF	20.2	21.4	60.0	29.1	18.5	21.4
	RIT	35.2	37.1	150.0	62.3	41.2	42
	RIT-RIF	15.0	15.7	90.0	33.2	22.7	20.6
Frontal outer	ROF	22.2	37	28.1	20.6	21.8	17.2
	ROT	68.2	80.9	230.6	23.4	48.4	47.1
	ROT-ROF	46.0	43.9	202.5	2.8	26.6	29.9
Sagittal distal	RDF	36.2	34.5	54.4	48.4	21.4	29.2
	RAT	96.1	51.6	194.3	60.3	62.5	117.6
	RAT-RDF	59.9	17.1	139.9	11.9	41.1	88.4
Sagittal distal-post	RPF	24.7	22	17.2	22	22.3	22.7
	RPT	66.2	165.7	45.1	102.8	33.7	385.0
	RPT-RPF	41.5	143.7	27.9	80.8	11.4	362.3
	BS	39.2	47	42.7	45.8	46.2	

NexGen Legacy (Zimmer, Warsaw, IN, USA); BM Deluxe (Beijing Montagne, Zimmer), Hermes Hifit (Ceraver, Roissy, Cedex, France), Genesis 2 (Smith & Nephew, Memphis, TN, USA); Guided Motion = experimental design; BS = bearing spacing; R = anterior femoral radius; RDF = distal femoral radius; RPF = distal-posterior femoral radius; ROF = outer femoral radius; RIF = inner femoral radius; RAT = anterior tibial radius; RPT = posterior tibial radius; ROT = outer tibial radius; RIT = inner tibial radius.

surface models produced by the digitizing described previously (Table 1). All of the TKA samples consisted of a cobalt-chrome femoral component and a polyethylene tibial component. The fifth design was an experimental PS type of knee designed to reproduce the mechanical characteristics of the anatomic knee. This design had relatively close femorotibial constraint medially and low constraint laterally, whereas the cam-post surfaces were rounded to accommodate the internal-external rotations without corner contacts. For reference in this study, this design was called the Guided Motion. The components were made from the computer model using a hard plastic resin.

Two methods were used to display the motion data. First, the contact patches, their sizes estimated from the finite element study, were depicted on overhead views of the tibial bearing surface. For each TKA, five such diagrams were shown for compression only (neutral path of motion), anterior shear force, posterior shear force, internal torque, and external torque. From these visuals, the displacement of the contacts in the flexion range, the AP displacements and internal-external rotations, the proximity of the contact areas to the edges of the plastic and on the post, and the effect of the cam-post on the motions could be visualized.

Second, graphs were drawn of the distance of the centers of the lateral and medial contact points from the posterior of the tibial component for the lateral and medial sides. These data were used to plot the neutral path of motion for the flexion range. The laxities for anterior and posterior displacements were superimposed on this neutral path. Similar plots were made for the neutral path of rotation and

the rotational laxities. It is noted that plotting the displacements of contact points is almost identical to plotting the rigid body motion of the femoral component based on a transverse circular axis except for closely conforming bearing surfaces [21, 30]. For that reason, for the Guided Motion design, the rigid body motion based on the circular axis was plotted for the medial displacements.

To provide a benchmark for evaluation of each TKA, we replotted the data from a previous study [29] in which cadaveric knee specimens were tested using a similar protocol as the present experiments. The test machine was an earlier version of the present machine but with the same operating principles. The actual forces applied in the tests were not exactly the same however, but sufficiently similar to allow for comparisons in general motion characteristics. The premise was that a TKA should reproduce similar motion characteristics to that of the anatomic knee.

Results

Differences in Motion Characteristics Between Posterior-stabilized Total Knees

The important geometrical parameters of the bearing surfaces were defined and measured on the five total knees (Fig. 2; Table 1). The motion data is shown as contact point locations (Fig. 3) and numerically showing the displacements of the neutral path of motion with flexion and the laxities about the neutral path (Figs. 4, 5). The neutral

Fig. 3 The contact areas for the different PS designs in the range of tests. The neutral column is for compressive load only. The other four columns show data for AP shear forces and for internal and external torques. The colors of the contact areas indicate flexion angle.

path data (Fig. 3, column 1) showed the AP progression of the contacts with flexion and the amount of symmetry of the contact points between lateral and medial. The differences between the anterior and posterior columns indicated the amount of AP laxity, largest for the Deluxe and smallest for the Genesis and Guided Motion. The difference between the internal and external columns showed rotational laxity, which was relatively small in high flexion as a result of the cam-post and posterior tibial plastic interaction. Posterior edge contacts were noted in some cases. The neutral path of motion showed closely equal lateral and medial posterior displacements in the flexion range for the Legacy (14 mm), the Deluxe (12 mm), Hermes (20 mm), and Genesis (6 mm). For the Guided Motion, the lateral value was 15 mm and the medial value 5 mm. All knees showed posterior displacement after cam-post contact occurred.

To interpret the influence of the sagittal radii on the AP laxity, a simple equation is used: for a compressive force C , shear force S , tibial radius R , femoral radius r , the AP laxity $e = (R-r)\sin \theta$ where $\tan \theta = S/C$. Hence, the AP laxity of the components is proportional to the difference between the tibial and femoral sagittal radii (Table 1). This

is consistent with in vivo kinematics of TKA [14]. In our test, soft tissue restraint would reduce the AP laxity values slightly. Small AP laxity in extension was related to the small radii difference, especially notable in the Genesis. In early to midflexion, large AP laxity was related to large radii differences, noted in the Deluxe, Legacy, and Genesis. For the Deluxe, with the largest radii difference, there was even posterior subluxation (Fig. 4). In higher flexion, all AP laxities were reduced as a result of the restraining action of the cam-post. In rotation, the laxity was also related to the sagittal radii difference except for the Genesis, which was found to be restricted by low clearance between the femoral housing and the plastic post. The rotational laxity of the Hermes averaging 22° was enhanced by the large frontal tibial radii. The Genesis and Guided Motion showed relatively small rotations averaging 9° , partly as a result of post constraints, and in the case of the Guided Motion, to the small radius difference on the medial side. All designs showed a reduction in rotational laxity at 120° flexion, observed to be the result of the “entrapment” of the posterior femoral condyle between the posterior of the plastic post and the posterior lip of the tibial bearing surfaces.

Fig. 4 The neutral path of motion and the AP and the laxities about the neutral path for the lateral and medial contact points. The data for the lateral and medial condyles are superimposed to indicate the amount of symmetry.

Reproducing Anatomic Kinematics

For comparison with the total knees, the average data from a previous study on eight anatomic knees [30] with similar loading conditions were replotted (Fig. 6). In these anatomic knees for the neutral path, the medial side was at almost a constant location, but on the lateral side, there was progressive posterior displacement of 21 mm with flexion. With AP forces, there were only small displacements medially but total laxities of between 3 and 8 mm laterally. The average rotational laxities of the anatomic knees ranged from a minimum of 13° at 0° flexion to a maximum of 25° at 30° flexion with an average over the flexion range of 18°.

A major difference among the Legacy, Deluxe, Hermes, and Genesis, from the anatomic, was that the posterior displacement of the neutral path during flexion was equal for the lateral and medial sides, ranging from 6 to 20 mm for the different designs. The AP laxities followed the same

pattern, being equal between lateral and medial, of magnitudes in the range 12 to 23 mm. In contrast, in the anatomic knee, the laxity on the lateral side was between 3 and 8 mm but less than 2 mm medially. The rotational laxities were similar to anatomic for the Legacy, Deluxe, and Hermes, but only approximately half of anatomic for the Genesis and Guided Motion.

The Guided Motion design did show larger lateral (15 mm) than medial (5 mm) posterior displacement of the neutral path over the flexion range, reflecting the higher medial conformity. The lateral AP laxities were similar to anatomic, but on the medial side, the values were higher than anatomic. The rotational laxities were only half of the normal on average.

Discussion

Functional performance is receiving increasing attention as an important outcome measure after TKA. One particular

Fig. 5 The neutral paths of motion in rotation and the internal-external laxities about the neutral path.

clinical followup study indicated that in terms of patient satisfaction, certain design types were preferred to others, indicating that design is likely to play an important role [23]. Preclinical laboratory methods have an important role in that they can provide direct comparisons between different designs independent of the numerous surgical and patient variables [6, 7] and also be used at the preclinical design stage. One particular test method that focuses on the constraint and laxity of the TKA itself is embodied in an ASTM standard [1, 12, 20] on the basis that the inherent stability of the implant and the laxity boundaries will relate to functional ability. As a benchmark, the measurements of laxity can be directly compared with that of the anatomic knee itself. Our test machine was designed to carry out this ASTM test, extending it by testing at a range of flexion angles from 0° to 120° and including simulated soft tissue restraint. We used the output motion data to compare four commercial PS designs and one asymmetric PS design and found distinct differences, which were evidently related to the geometry of the bearing surfaces and cam-post design.

We also compared the motion data with that from anatomic knee specimens tested under similar conditions in a previous study and found that the asymmetric design more closely matched anatomic overall, although there were still some differences. It is noted that this is a different type of test than simulating actual functions [22, 24, 32], although the test is intended to encompass the extremes of motion in a spectrum of functions. However, the test does not extend to the variations in surgical placement, ligament tensions, and functional loading conditions [6, 7].

In relation to the research questions, the testing method was ideal in that it measured the motion characteristics of different designs under exactly the same loading conditions. To what extent such in vitro tests relate to in vivo conditions has been addressed in detail [25]. These authors pointed out the complexities involved with comparing the vast literature of in vitro and in vivo kinematic studies but concluded that overall, there was a parallel between many of the different motion parameters, including the AP displacements and axial rotations. The authors also noted the

Fig. 6 The neutral paths of motions and the laxities about the neutral path using the transverse circular axes for eight knee specimens tested using a similar loading sequence to that used for the PS designs [29].

value of measuring neutral paths of motion and laxity about the neutral path. One particular indicator that total knee geometry affects kinematics *in vivo* was that the motion of PS designs was less variable and involved less AP laxity than for CR designs, the former designs being generally more conforming than the latter [2].

Our study did not systematically study the effect of particular geometrical parameters on motion but instead measured particular trends on specific commercial designs and one experimental design. It was clear that in general terms, sagittal conformity affected the AP laxity in these PS designs, but the actions between the femoral housing and tibial post played a major role also. The interaction occurred in both early flexion and after cam-post engagement in flexion, consistent with *in vivo* fluoroscopic data [14, 16, 17]. The rotational laxity was similarly affected by the sagittal conformity and the cam-post interaction, but also by the frontal geometry. A systematic investigation of multiple geometrical parameters has been described previously for a cruciate-retaining type with posterior cruciate ligament retention [32]. An objective function was defined

based on various laxities of the TKA. The goal was to determine the group of geometrical design parameters that minimized the difference between this objective function with that of the same laxity function in anatomic knees. In that respect, we are using a similar approach in our study, although only applied to particular knee designs. The authors also investigated a larger lateral tibial sagittal radius than medial. Another approach to quantifying TKA motion was to develop a lower limb model of the knee with muscles and ligaments and analyze the squat function, which was compared with data from a crouching machine [6, 11]. They found that sagittal motion and contacts were dependent on implant geometry, but that motion was also affected by surgical and patient-related variables. This work provided an important connection among laboratory test machines, computer models, and the *in vivo* situation.

The testing method we used was useful for examining a new design concept. The motion characteristics were not ideal but did point to design modifications, which would produce closer motion to the anatomic knee. However, it may be that within the design form of a cam-post design, it

may not be possible to achieve anatomic motion exactly. However, computer models such as referenced here [6, 32] could be applied to determine the geometrical parameters for the closest match.

In conclusion, we measured the motion parameters of various PS total knees by applying combinations of compression, shear, and torque forces at a range of flexion angles. There were large differences in the motion, which were related to differences in geometries of the bearing surfaces and the cam-post. There was an indication that an asymmetric design was able to produce the asymmetries in motion of the anatomic knee tested under similar conditions. Further work is indicated to optimize asymmetric PS designs to determine how closely anatomic motion can be achieved. This can be approached by physical testing or computer models and ultimately in clinical trials.

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