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Tibiofemoral Contact Stress and Stress Distribution Evaluation of Total Knee Arthroplasties

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Abstract: The Fuji film (Itochu, Los Angeles, CA) area analysis technique demonstrates that a more accurate assessment of tibiofemoral contact stresses is possible when the film is used at 37°C and at the upper end of its sensitivity range (in this case, a 2,000-N load). An AMK with a regular and Hylamer-M insert (DePuy, Warsaw, IN), an MG II (Zimmer, Warsaw, IN), an Omnifit (Osteonics, Allendale, NJ), an Ortholoc III (Dow Corning Wright, Midland, MI), a PCA II (Howmedica, Rutherford, NJ), and a PFC (Johnson & Johnson Orthopaedics, Raynham, MA) had average contact stresses that varied only 12% at 60° flexion. At 0°, 15° and 60° flexion, stresses ranged from 13 to 25 MPa. Contact area distribution ratios, which were smaller at 37°C than at 24°C, provide a quantitative means of grouping implants according to the shape of the tibiofemoral contact area. The Omnifit, MG II, PCA II, and PFC had small ratios (symmetric areas). The AMK and Ortholoc III had large ratios (asymmetric contact areas). If the impression is reflective of wear, it would be expected to be focal in knees with small ratios and contact areas, and uniform in knees with large ratios and contact areas, whereas large ratios and small areas would imply a linear wear pattern. Calibrated electrical resistance contact stress measurements indicated that the Fuji film measurements underestimated the magnitude of contact stresses. They also provided a means of quantifying the rate of area increase during initial loading of the knees, with the highest area increase noted for the knee with the roughest insert (Ortholoc III) and the lowest area increase for the knee with the smoothest insert (PCA II). **Key words:** tibiofemoral contact stresses, contact geometry, artificial knee.

Prior to the advent of metal-backed tibial trays, aseptic loosening was the primary mode of failure of total knee systems.[1-4] Aseptic loosening was linked to polyethylene tray flexibility,[4,5] and metal backing was shown to reduce the stresses in the underlying trabecular bone.[4,6,7] With the reduced incidence of loosening noted since the introduction of metal-backed trays, polyethylene wear now appears to be the limiting factor in the longevity of total knee systems.

Several experimental approaches have been used to study the wear of polyethylene inserts. The use of wear testers, which cyclically or continuously load insert materials,[8-10] provides an indication of the relative wear resistance of various preparations of polyethylene, but does not provide information about clinically expected locations and patterns of wear. Computer-based stress analysis offers extensive information about stresses in the knee and how they are affected by implant shape and size, but has been limited to the analysis of only one or two implant designs,[7,11,12] possibly because of model preparation time. Similarly, wear simulators, which

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model muscle forces and body weight loading of components, require complex dedicated servohydraulic testing systems. Time-consuming wear testing can last more than 2 months to complete 10 million cycles, making comparison of several clinically available implant designs in a number of sizes prohibitive.

Stress analysis using pressure-sensitive Fuji films (Itochu, Los Angeles, CA) can provide a simple reproducible technique for comparing the contact stresses of various prostheses. It has been claimed that this can provide a means of inferring relative wear rates of clinically used implants as well as identifying the location and shape of expected wear areas.13–17 A correlation between contact stresses and wear generated during bench top testing has been noted.18 As such, it should be possible to use contact stress measurements to infer the extent of wear. This technique has not always accurately reflected wear patterns observed on clinical retrievals.9,19,20 In fact, wear patterns have often been noted to vary, even for implants of the same design, suggesting that factors such as materials properties21,22 and subsurface stresses also contribute to the extent of observed wear.

The purpose of this study was to examine the sensitivity of the Fuji film contact stress analysis technique to loading time, peak load, and temperature in various total knee arthroplasty designs. These measurements were collected to determine possible inaccuracies that could have led to the poor correlations noted with clinical retrievals. Contact geometry of the film impressions was also examined and described quantitatively. In addition, an electrical resistance-based contact area analysis technique, which was sensitive enough to detect surface roughness, was used to assess contact areas as another means of examining the accuracy of the Fuji film technique.

Materials and Methods

Mechanical Testing Technique

Intermediate-sized total knee implants were obtained from six manufacturers. Component sizes used were those specified by company representatives (Fig. 1, Table 1). Femoral components were press-fit onto composite synthetic femurs (Pacific Research Laboratories, Vachon Island, WA). A knee loading fixture (Fig. 2) was designed that placed the femoral components in 4° to 6° valgus relative to the anatomic axis of the synthetic femurs. Tibial components were mounted on blocks with an initial neutral alignment with respect to the coronal and sagittal planes. Final alignment was adjusted by iteratively (1) loading each knee system, (2) measuring the areas of the lateral and medial impressions, and (3) adjusting the tibial component within the 2° range that maintained the femoral component in alignment until the most similar lateral and medial compartment impressions were obtained. Front-to-back alignment of the knees was initially set with the knee at 0° flexion, using the relative tibiofemoral position of an intact knee.[23] The change in alignment in this plane was dictated by the fixture, which was designed to simulate changes in the center of rotation and relative positions of the femoral and tibial component in accordance with studies of the intact knee.[23]

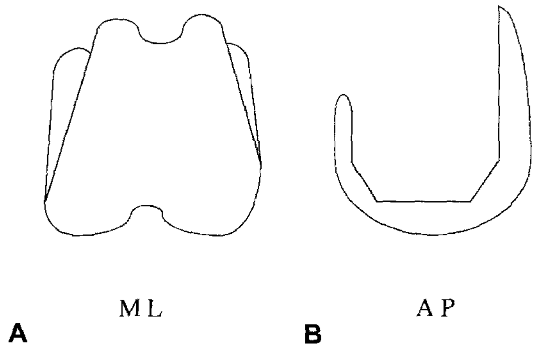

Fig. 1. (A) Front and (B) side views of the various knee systems described.

Components were tested on an MTS servohydraulic test machine (Materials Testing System, Minneapolis, MN) in load control. Initial studies using the Fuji film technique with loads lasting 10, 30, and 60 seconds indicated no significant difference in contact area or contact profile. In subsequent testing, a 10-second contact time at the predetermined load was used. Knees were tested at loads of 667 and 2,000 N (68 and 204 kg) in 0°, 15°, and 60° flexion. Each test series was carried out at 24°C, to allow comparison with published results, and at 37°C, to allow evaluation of stresses at physiologic temperatures. Testing was also performed at 55°C to provide a third set of measurements to assess the temperature sensitivity of stresses for each implant.

For each test run the femoral component was mounted at the desired flexion angle and the polyethylene insert was heated in distilled water to 60°C and then mounted on the test machine. Testing was carried out at each test temperature as the surface of the insert in the region of contact of the condyles cooled to 24°C. Surface cooling rates were determined from thermocouple measurements collected from the surface of the inserts in the region

Table 1. Component Dimensions of the Different Knee Systems Described

		Component Sizes			Component Dimensions (mm)		
Manufacturer	Knee	Femoral	Tibial	Insert	Femoral ML Dimension	Femoral AP Dimension	Insert Thickness
Depuy	AMK*	3	3	3	66	64	8
	AMK†	3	3	3	66	64	10
Dow Corning Wright	Ortholoc III	Medium	Medium	Medium	62	56	8
Howmedica	PCA II	Medium	Medium	Medium	65	58	9
Johnson & Johnson	PFC	3	3	3	66	61	8
Osteonics	Omnifit	7	7	7	63	59	8
Zimmer	MG II	4	D/yellow	C,D/yellow	65	59	9

The AMK was tested with both an *8-mm regular and †10-mm Hylamer-M insert. ML, mediolateral; AP, anteroposterior.

near the center of the condylar contact area and noted to average 1°C per minute during the testing period. Testing was also carried out at 24°C after an extended cooling period to assess the effect of potential temperature gradients on the contact stress measured from the inserts. To ensure reproducibility, each test series was rerun three times.

Two techniques were used to evaluate the tibiofemoral contact areas from which stresses were calculated: (1) a Fuji contact print technique, and (2) an electrical resistance contact area measurement technique.

Fuji Film Studies

The Fuji film testing technique involved the use of a two-part medium-grade pressure-sensitive Fuji film. This film is sensitive to pressures of 9.8 to 49.0 MN/m^2 (MPa). After a sheet of the two-part film was placed between the femoral and tibial components, it was loaded. This resulted in two impressions, one created in the lateral compartment and one in the medial compartment.

Fuji contact prints were evaluated using an optical image analysis system. This system consisted of

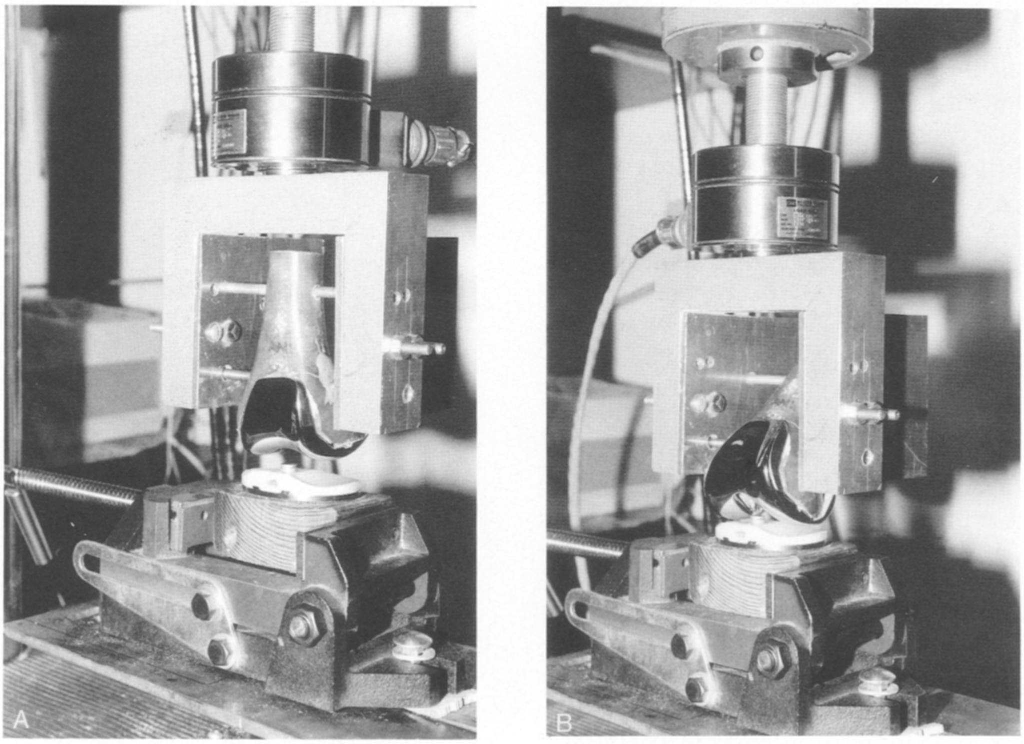

Fig. 2. Design of the fixtures used to load the knee systems. The femoral component shown at the (A) 0° flexion angle and (B) 6° flexion angle.

a Sony black and white camera (model AVC-D7 CCD, Tokyo, Japan) coupled to a Image Grabber Board (Data Translation, Marlboro, MA) in a Macintosh IIcx computer (Apple Computer, Cupertino, CA) with a color graphics card and gray-scale monitor. Images were collected using a modified version of Image, a software package provided by National Institutes of Health (Research Services Branch, National Institute of Mental Health, Bethesda, MD). This system was used to assess overall contact area and the moment of inertia of the contact area about the sagittal and the coronal planes.

The images were independently analyzed by two investigators. First, each investigator adjusted the threshold level in the Image software to incorporate the edge of the contact impression. The digitally characterized threshold level was then applied during each image evaluation process. Images were captured and evaluated twice by each investigator to ensure consistency of this process. In addition, the accuracy of the imaging system was assessed using an ellipse with a known area and moments of inertia.

The image analysis software calculated the area and moment of inertia I_{yy} about the coronal (medial/lateral) plane and the moment of inertia I_{xx} about the sagittal (anterior/posterior) plane (Fig. 3). These values were copied into Excel (Microsoft, Seattle, WA) spreadsheets for data reduction and statistical analysis. Contact stresses were calculated from contact areas by adding the lateral and medial contact areas and dividing the total into the applied load (stress = load/total contact area). The ratios of moments of inertia (Fig. 4) about the coronal and sagittal planes (I_{yy} and I_{xx}, respectively) were assessed and used to group the components by asymmetry of distribution of the contact area. These areas were named area distribution ratios. Ratios above 2.5 were considered asymmetric, and those below, symmetric. The average areas, area distribution ratios, and stresses with their respective standard deviations were plotted as bar graphs using Cricket Graph (Cricket software, Computer Associates International, Islandia, NY).

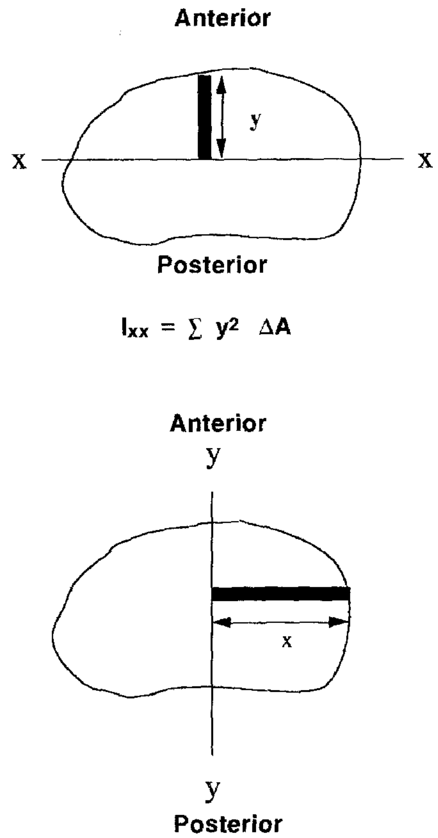

Fig. 3. Description of the way in which moments of inertia of imprints were assessed. Top: Evaluation of the moment about line xx, the line separating the anterior half of the insert from the posterior (coronal plane). Bottom: Evaluation of the moment about line yy, the line separating the medial compartment of the insert from the lateral (sagittal plane).

Electrical Contact Resistance Measurement Technique

Polyethylene tibial inserts were made electrically conductive by coating them with a 400-Å gold/palladium layer. This was done using a Bio-Rad E5100 series II cool sputter coater (Bio-Rad, Polaron Division, Cambridge, MA). This coating allowed the measurement of the electrical resistance between the femoral components and the tibial inserts when they were in contact. For each knee system, a wire was attached to the coated polyethylene insert in the region of the intracondylar eminence and to the femoral component in the trochlear notch. During loading the electrical resistance across the tibiofemoral contact was continuously monitored. Load values were measured from the test machine through an IDAC (International Data Acquisition and Control, Amherst, NH) board, which was connected to a Macintosh IIsi computer (Apple Computer) running MacControl software (Small Business Computers of New England, Amherst, NH). The load and resistance measurements were imported into a spreadsheet to carry out data reduction and statistical analysis. Initial resistance values for each component varied according to exact placement of the electrical leads. Therefore, resistance measurements were normalized by dividing each by the peak resistance recorded. The electrical measurements were then transformed into area measurements by using information from the calibration procedure that follows.

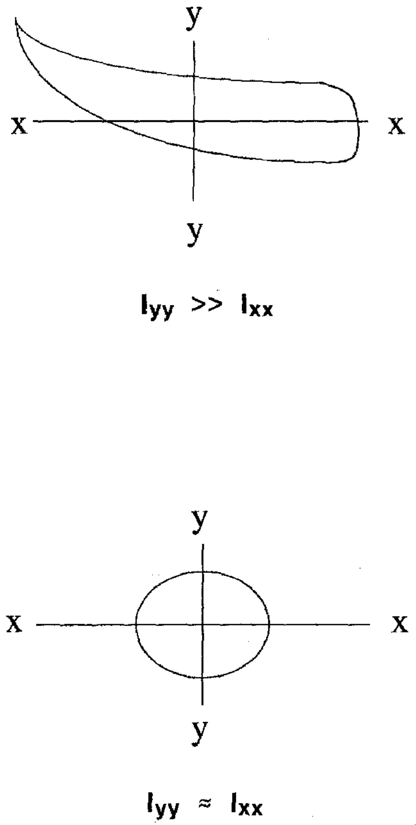

Fig. 4. The ratio of the moments of inertia I_{yy}/I_{xx} represents the area distribution ratios. For example, a line of contact would have a ratio much larger than 1 (ie, I_{yy} is much larger than I_{xx} so that $I_{yy}/I_{xx} >> 1$), whereas a circular contact area would have a ratio equal to 1 (ie, I_{yy}=I_{xx} so that $I_{yy}/I_{xx} = 1$). Top: I_{yy}/I_{xx} will always be larger than 2.5. Bottom: I_y/I_x will be greater than or equal to 1 but always smaller than 2.5.

A flat ultrahigh-molecular-weight polyethylene (UHMWPE) sheet was made electrically conductive by applying a 400-Å gold/palladium layer. An electrical lead was attached to the edge of the sheet. Five precleaned laboratory microscope slides (Fisher Scientific, Pittsburgh, PA) were cut so that they had surface areas of 100, 50, 25, 15, and 7 mm^2. These were coated with a 400-Å gold/palladium layer, and electrical leads were attached to each using a silver conductive paint (GC Electronics, Rockford, IL). The coated UHMWPE sheet was placed on a universal pivot attached to the lower actuator of an MTS machine. Sequentially, in order of descending area, each coated glass sheet was glued to a universal pivot on the load cell of the test machine. During loading, the electrical resistance between the two coated surfaces was continuously monitored. Load values were measured from the test machine through an IDAC board, which was connected to a Macintosh IIsi computer running MacControl software. The load and resistance measurements were imported into a spreadsheet.

Resistance measurements collected at 5 MPa were plotted as a function of area. The slope of the resulting linear plot was used to translate the electrical measurements collected during testing of knee implants into area. The areas derived from the electrical contact resistance measurements were compared with Fuji film measurements, and the relationship between areas described by both techniques was examined.

Results

Accuracy of Fuji Film and Image Analysis System

Comparison of areas measured from films loaded for 10, 30, and 60 seconds indicated a difference of less than 6% between areas from 60-second loading periods and those from 10-second loading periods. No significant difference in contact area with contact loading times was found. A comparison of tests run prior to heating at 24°C with those run following cooling to 24°C from 60°C produced contact areas that were not significantly different. Surface cooling rates were recorded and noted to average 1 degree per minute during the testing period, suggesting that inserts were at a relatively homogeneous temperature immediately prior to testing. To minimize temperature changes during testing, all testing was carried out with a 10-second holding time.

Microscopic examination of the Fuji film surfaces loaded to 667 and 2,000 N revealed that the impressions were the result of numerous contact points between the femoral component and the tibial insert surface. At the higher test load, the total areas of the impressions were larger and the point contact densities were also higher. At the lower test load, the points of contact were distributed with significant space around each contact point (Fig. 5). Color density variation of the film resulted from the point contact density differences. The image analysis unit did not have the capability to measure the areas of individual points of contact. Although this might be done by using the image analysis unit through a microscope and collecting multiple images, this process would introduce other types of error to the measurement and would be prohibitively time consuming. As such, the image analysis program treated the density gradient within one impression

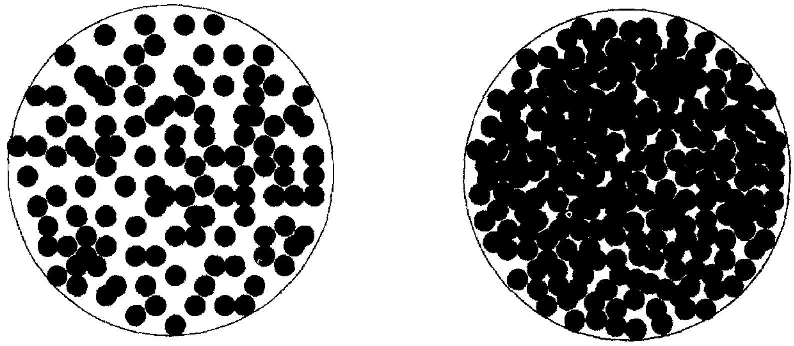

Fig. 5. Appearance of characteristic fields from two Fuji contact prints viewed at × 95 on a stereo microscope. Left: After a 667 N load. Right: After a 2,000 N load.

as if the entire area were in uniform contact. It converted the impressions to a gray-scale map, resulting in an error of approximately 35% in the area for knees loaded to 667-N in comparison to those loaded to 2,000-N. As such, measurements from knees loaded to 2,000-N provide a substantially more accurate indication of contact stresses when using the medium-grade film.

Errors associated with relative insensitivity of the Fuji film to pressures below 9.8 MPa (the low end of the pressure range over which Fuji certifies the accuracy of the film) were not quantified. This error would not be higher when using the higher load during testing, and it should be lower, since the impressions collected at the lower load created larger areas at lower contact stresses. To most accurately compare the average contact stresses, only the measurements from the 2,000-N loading studies were used. Inaccuracies induced by the resolution of the image analysis camera and edge detection software and the combined analysis software and operator error were determined to be 3% when assessing the area and moments of inertia of a filled ellipse.

Fuji Film Area and Area Distribution Measurements

All results presented are for the 2,000-N test load. Medial contact areas were generally slightly larger than lateral contact areas. At 37°C, medial compartment contact areas ranged from approximately 37 mm^2 (for the Omnifit [Osteonics, Allendale, NJ]) to 80 mm^2 (for the Ortholoc III [Dow Corning Wright, Midland, MI]). Lateral compartment contact areas showed greater variability and ranged from 32 mm^2 (for the AMK with a Hylamer-M insert [DePuy, Warsaw, IN]) to 96 mm^2 (for the Ortholoc III) (Fig. 6). Contact areas for the lateral compartment, in particular, were most similar at 60° flexion and had the greatest variability between implants at 0° flexion. In all cases, the increase in contact area with temperature was linear and was a function of the component being tested (Table 2).

The contact area of the Ortholoc III showed the smallest area increase with temperature (0.95% change per degree centigrade), whereas the AMK with the Hylamer-M insert, and the Omnifit and the PFC (Johnson & Johnson, Orthopaedics, Raynham, MA) showed the most marked increase in area with temperature (1.99, 1.89, and 2.10% change per degree centigrade, respectively). For a temperature difference of 13° (between 24°C and 37°C), this represents a difference ranging from 13.3% for the Ortholoc III to 34.8% for the PFC.

The shape of the contact areas was different for the lateral and medial compartments, as might be expected, because the lateral and medial condyles of the femoral components tested had different shapes. The contact areas varied from highly symmetric areas (slightly elliptic areas of contact) for the PCA II (Howmedica, Rutherford, NJ) to highly asymmetric areas (lines or patches of contact) for the Ortholoc III. Symmetric areas of contact were considered to have I_{yy}/I_{xx} ratios less than 2.5, and asymmetric areas of contact were considered to have higher I_{yy}/I_{xx} ratios. The contact area distribution ratios (I_{yy}/I_{xx}) defining the asymmetry of the area of contact of the implants ranged from 2 (noted for a slightly elliptic area of contact) to 50 (noted for a thin line of contact) for testing run at the 60° flexion angle (Fig. 7).

The contact area distribution ratios decreased with increasing temperature, indicating that contact areas became more uniformly distributed as temperature increased. The contact area distribution ratios were different for the lateral and medial compartments and varied as a function of flexion angle from 1 to 42 for testing carried out at 37°C. The highest contact asymmetries (those above 30) were noted for the Ortholoc

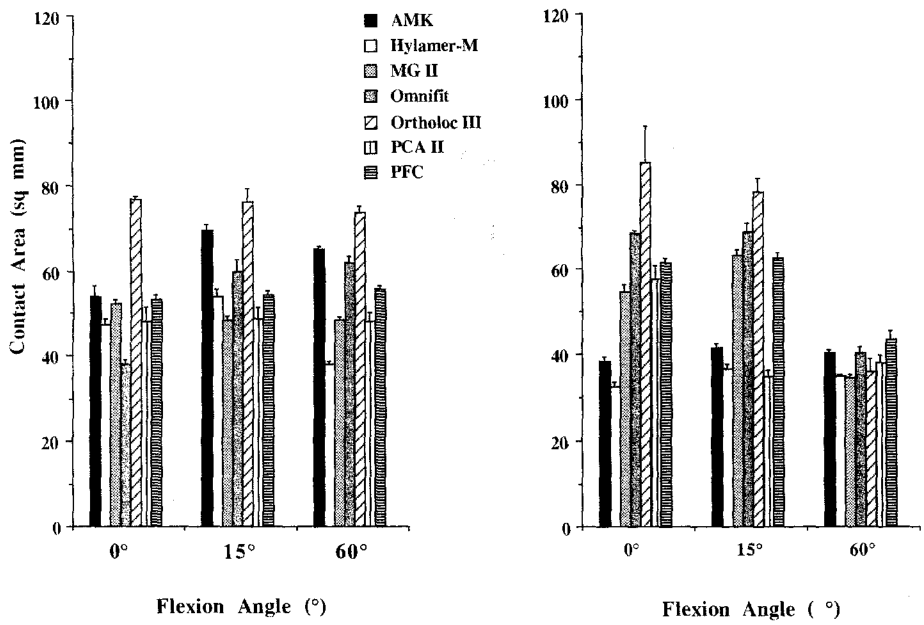

Fig. 6. Contact areas in the medial and lateral compartments for the components tested at 37°C. Left: Medial contact area versus flexion angle; loaded to 2,000 N. Right: Lateral contact area versus flexion angle; same load.

III at 0° and 60° flexion and for the AMK at 15° flexion. The lowest contact asymmetries (those below 5) were noted for the PCA II at all flexion angles and for the AMK at 0° flexion (Fig. 8).

Contact Stress Analysis Using Fuji Film Measurements

At 24°C, contact stresses ranged between 12 and 28 MPa. The lowest stresses occurred at the 15° flexion angle for all knees except the Ortholoc III and PCA II. The highest stresses were noted at the 60° flexion angle for all knees, except the AMK with the regular insert and the AMK with the Hylamer-M insert. At 37°C, contact stresses ranged between 13 and 25 MPa, with the lowest stresses at the 15° flexion angle for all knees except the PCA II (Fig. 9). The highest contact stresses were at the 60° flexion angle for all knees except the AMK with a regular insert, which experienced the highest stresses when tested in full extension (ie, 0° flexion). At 55°C, contact stresses ranged between 12 and 21 MPa and were lower at the 0° and 15° flexion angles than at the 60° flexion angle for all knees except the AMK with the regular insert.

Contact stresses for all components decreased as temperature increased (Fig. 10). Differences between the contact stresses of the six components tested were the most pronounced at 24°C.

Electrical Contact Resistance Measurements

The curves of contact resistance versus load for each of the glass calibration fixtures leveled off at specific resistances. The resistance versus area calibration curve plotted using the resistance values

Table 2. Total Contact Area Increase With Increasing Temperature for Testing at 60° Flexion

Component	Area (mm²) 24°C	37°C	55°C	Area Δ/°C (mm/°C)	Δ Area/°C (%)	Δ Area from 24°C to 37°C (%)
AMK						
Regular insert	87.6	105.3	127.0	1.27	1.45	16.82
Hylamer-M insert	54.2	72.8	88.0	1.08	1.99	25.53
MG II	70.3	82.8	101.3	1.00	1.42	15.19
Omnifit	79.3	102.4	126.1	1.50	1.89	22.53
Ortholoc III	92.9	109.5	120.7	0.88	0.95	15.15
PCA II	75.0	85.9	113.3	1.25	1.67	12.64
PFC	75.1	99.3	122.4	1.51	2.01	24.31

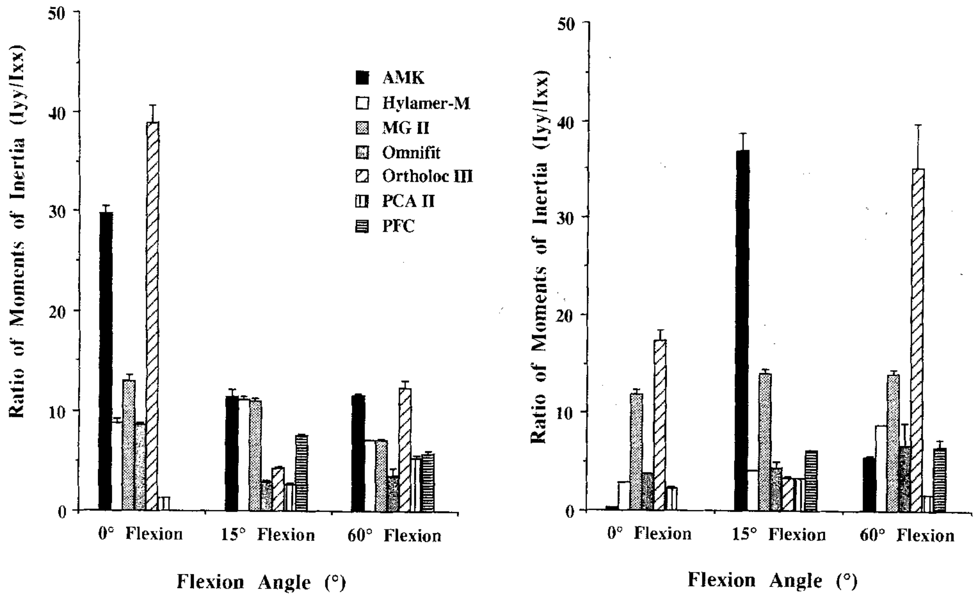

Fig. 7. Area distribution ratios in the (left) medial and (right) lateral compartments for the components tested at 37°C. Loaded to 2,000 N. Large ratios represent line contact.

assessed at 5 MPa from each glass calibration square produced a linear relation with a slope of -2.1 and an intercept along the resistance axis of 149.

The initial electrical resistance measured from each knee system was different because of slight differences in the placement of wires necessitated by knee design. All curves had a similar shape. The variations in the initial slopes of resistance with load were broader than those in the final slopes, which were nearly asymptotic to the load axis. If the initial portion of the curve is considered to represent the crushing of high spots or asperities on the insert surface, the final portion of the curve will represent contact with the flattened surface of each insert. The slopes of graphs normalized to the final portion of the curves and converted to area versus

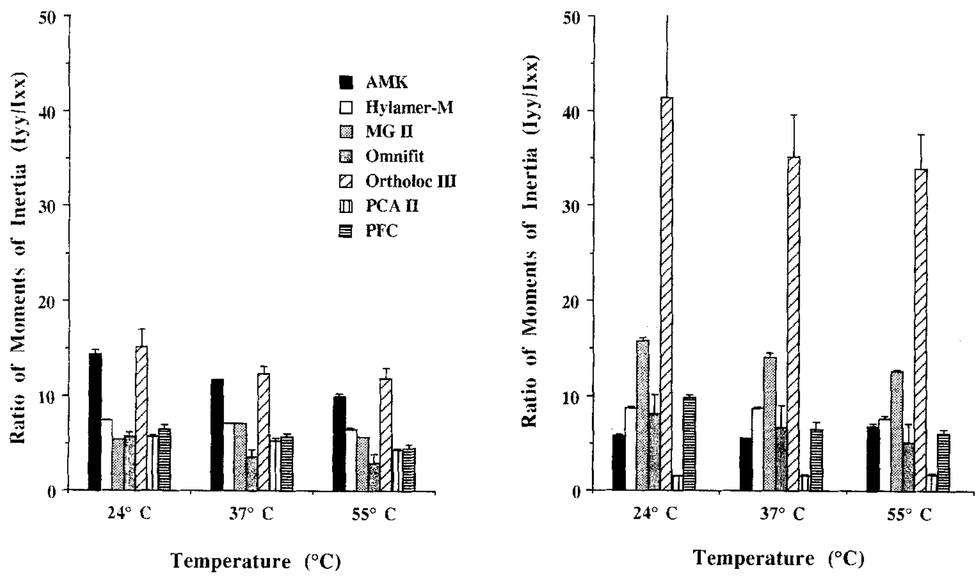

Fig. 8. Area distribution ratios in the (left) medial and (right) lateral compartments for the components tested at 60° flexion. Loaded to 2,000 N. Large ratios represent line contact.

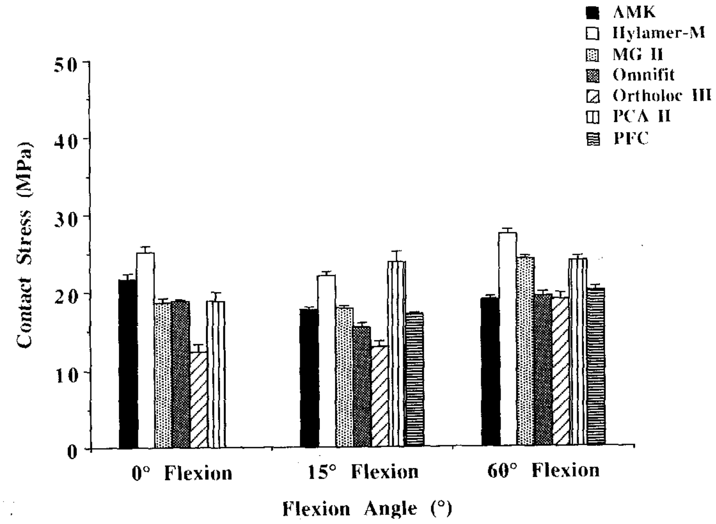

Fig. 9. Contact stresses as a function of flexion angle at 37°C. Loaded to 2,000 N.

load curves by using the calibration information indicated that the contact areas of the Omnifit and Ortholoc III were the highest. This made the contact stress on these inserts (Table 3) the lowest at 21 MPa. By use of this technique, the contact stress for the PCA II was determined to be the highest at 58 MPa (Table 3). These values, which are based on the terminal slopes of the curves, correlated with Fuji film information, although the contact stresses were higher than those measured from the Fuji film impressions.

The slopes of the initial segments of the electrical resistance curves agreed with visually observed surface roughness of the polymer inserts. The smooth heat-treated surface of the PCA II resulted in an initial slope that did not change substantially with load and had an initial rate of contact area increase with load of 0.16 mm^2/kg (Table 3). The machined surface of the insert of the Ortholoc III which was visibly the roughest insert, showed a change of area with load at the rate of 16.8 mm^2/kg (Table 3).

Discussion

Previous work has shown that the synthetic bones used in this study have properties similar to and more consistent than those of cadaveric bone.[24] Implants were easily press-fit onto these bones, and attachment to the test fixture was reproducible.

Preliminary testing of specimens using Fuji film to determine the contact area between femoral and tibial components with different contact times indicated no significant differences between contact

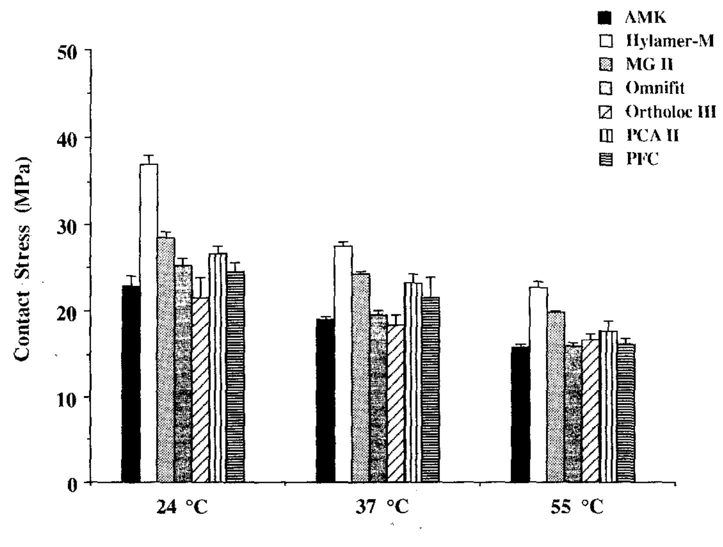

Fig. 10. Contact stresses as a function of temperature at 60° flexion. Loaded to 204 kg.

Table 3. Comparison of Electrical Resistance and Fuji Film Results at 60°

Knee	Stress: Electrical Resistance (MPa ± 11%)	Stress: Fuji Film (MPa ± 9%)	Rate of Area Change per Unit Load Change (mm²/kg ± 14%)
AMK			
Regular insert	35.0	20.2	0.82
Hylamer-M insert	30.0	26.0	0.48
Omnifit	21.0	17.5	1.88
Ortholoc III	21.0	14.9	16.80
PCA II	58.0	24.0	0.16
PFC	47.0	16.4	2.04

times at either load. The shortest holding period (10 seconds) was used during the remainder of the study to minimize the tendency of the polymer inserts to change temperature during testing. This approach overestimates the stresses on inserts by up to 6%, in comparison to situations when they are loaded for 1 minute. As such, it provides a more accurate reflection of a situation when a prosthesis is loaded during slow gait or short periods of stance.

When the Fuji film technique is used to assess contact area or contact geometry between a mirror-finished metal femoral component and a machined polyethylene insert, the asperities on the polyethylene surface come into contact with the film first. This leads to the speckled appearance of the film when it is used at relatively low loads. The image analysis system used in this study could not selectively calculate the area of these contact points. It calculated the area within an outer perimeter of contact. That perimeter was defined by the region where contact points on the film were detectable to the investigator collecting the measurements. As the areas between the contact points get smaller at higher test loads, the stresses calculated are more accurate. A comparison of the stresses calculated from measurements taken at 667 N and at 2,000 N showed that those taken at 667 N were lower by as much as 35%.

Polyethylene insert temperature also affects the accuracy of the measurements collected in modeling *in vivo* stresses. Temperatures as high as 55°C have been measured during simulated *in vivo* hip articulation.[25] Although it is likely that this is higher than temperatures in the tibial insert of an artificial knee, the 55°C test provided a third temperature point to allow assessment of changes in contact stress with temperature. For a temperature difference of 13° (between the 24°C and 37°C tests), difference in stresses ranged from 13.3 to 34.8%. This error is even larger if insert temperatures *in vivo* rise above 37°C during articulation.

Use of a calibrated film density scaling technique to assess the stress distribution offers potentially greater accuracy and should be considered when planning tests using Fuji films. While this approach requires additional calibration of the testing system and computer manipulation of the captured images, it can delineate regions of peak stress. Although the currently presented technique is substantially easier to use, information about peak stresses cannot be derived from it. The stress dependence of wear has been shown to be approximately linear to stresses below 10 MPa and exponential above this stress.[18] As the Fuji film used in this study was only sensitive enough to measure pressures above approximately 10 MPa, these areas would be expected to wear exponentially with increasing pressure.

The variation in results with flexion angle indicate that it is best to report stresses at a number of test angles. Contact stresses were generally the highest at 60° flexion and lower at lower test angles. At the 60° angle and 37°C, the AMK with a regular insert, the Omnifit, and the Ortholoc III had similar average contact stresses of about 18 MPa. The AMK with the Hylamer-M insert, the MG II (Zimmer, Warsaw, IN), the PCA II, and the PFC had similar contact stresses between 22 and 25 MPa. Average contact stresses were reduced and showed less variability between implants at higher temperatures. Since this testing reflects average stresses at body temperature, the work of Rostoker et al. again implies that all knees are operating at stress levels in which exponential wear with increasing stress is possible.[18]

Contact area distribution ratios provided a way of quantifying the shape of the contact area. Components with relatively symmetric or circular contact areas had a small contact area distribution ratio. At 60° flexion, these included the Omnifit, MG II, PCA II, and PFC. Inserts with both a small contact area distribution ratio and a small contact area would be expected to wear focally. Those with highly asymmetric contact areas had a large contact area distribution ratio. At 60° flexion, these included the

AMK and the Ortholoc III. Inserts with both a large contact area distribution ratio and a large contact area would be expected to undergo more uniform wear. Inserts showing a large contact area distribution ratio and a small area would be expected to show a line of wear across the insert.

The contact area distribution ratios decreased with increasing temperature, indicating that contact geometries become more circular at higher temperatures. The contact area distribution ratios of most of the knees tested showed no clear change with flexion angle. In a few cases, the ratios decreased as the flexion angle increased, indicating that contact geometries became more circular at 60° than they were at smaller flexion angles.

The rate of increase of the contact area with load corresponded to the visually observed roughness of the inserts. Rough inserts experienced a rapid increase in contact area, as would be expected if surface asperities were being crushed. Smooth inserts experienced a much slower increase in surface area with load. The plateau in the resistance curves suggested that asperities appeared to be completely crushed once a load of 1,177 N (120 kg) was reached. These measurements suggest that a load less than 1,177 N is inadequate to accurately assess the contact area of knee systems using an area averaging system. This technique also provided a means of identifying the initial surface roughness (which is related to the contact area at low loads) of polyethylene inserts. The slopes of the resistance at 1,177 kg provided a measure of the contact area and contact stress, which could be compared with the stresses calculated from use of the Fuji film technique. Electrical measurements suggested that Fuji film measurements overestimate the contact area. As such, they underestimate the contact stresses acting on the inserts.

In conclusion, this study has demonstrated that when physiologic conditions are modeled accurately (ie, testing is carried out at 37°C and a 2,000-N peak load), the Fuji film technique indicates that average contact stresses of various prostheses of similar dimensions are quite similar. Regardless of design, all inserts are operating near or beyond the yield point of polyethylene, which has been reported to range between 13 and 22 MPa[26-29] at room temperature. The yield point, however, has been shown to be as low as 12 MPa at elevated articulating temperatures in an oxidative environment.[27] The values measured also exceed the fatigue threshold of 10 MPa determined at room temperature.[30] Indeed, wear rates have been noted to be higher at elevated temperatures in oxidative environments,[27,31] and at the contact stresses measured in this study, all inserts would be expected to experience wear rates that could increase exponentially with increasing contact stress.[18]

The Hylamer-M insert, which had a geometry identical to that of a regular AMK polyethylene insert, experienced contact stresses ranging from 10 to 25% higher than those noted for other UHMWPE inserts. This is most likely because the polyethylene used to make this insert is stiffer. Although the yield point of Hylamer-M is reported to be 33% higher than that of the UHMWPE used to manufacture regular AMK inserts,[29] confirmation through wear studies and clinical trials will provide conclusive evidence whether the overall performance is comparable to or better than that of other inserts tested.

More conforming knee designs can potentially extend the life of total knee arthroplasties by reducing contact stresses. In addition, the development of new polymers that provide a combination of greater compliance and strength is required to reduce contact stresses and maximize the longevity of the polyethylene insert.

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