Identification of Cross-Sectional Parameters of Lateral Meniscal Allografts That Predict Tibial Contact Pressure in Human Cadaveric Knees

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To guide the development of improved procedures for selecting meniscal allografts, the objective of this study was to identify which cross-sectional parameters of a lateral meniscal allograft predict the contact pressure of the articular surface of the tibia. To meet the objective, the contact pressure of the articular surface of the tibia was measured with a lateral meniscal autograft and a lateral meniscal allograft using pressure sensitive film in 15 fresh-frozen human cadaveric knees. Allografts were matched only in transverse dimensions to the autograft but not in cross-sectional dimensions. Knees were loaded to 1200 N in compression at flexion angles of 0, 15, 30 and 45 degrees using a load application system that allowed unconstrained motion in the remaining degrees of freedom. Five cross-sectional parameters for both of the grafts in each of the anterior, middle, and posterior regions were derived from measurements obtained using a laser-based non-contacting three-dimensional coordinate digitizing system (3-DCDS) (Haut et al., J. Orthop Res, 2000). Five contact variables (i.e. the maximum pressure, mean pressure, contact area, and anterior-posterior and medial-lateral locations of the centroid of contact area) were determined from the pressure sensitive film. When each allograft was paired with the corresponding autograft, the root mean squared percent differences for the cross-sectional parameters ranged from a minimum of 28% for the width of the posterior region to 572% for the height of the posterior region. The root mean squared percent differences between the contact variables for paired grafts were 29% for the maximum pressure, 19% for the mean pressure, and 24% for the contact area. Differences in the cross-sectional parameters between the grafts were related to differences in the contact variables using regression analysis. Difference in the width was most often a predictor variable in the regression models with R^2 values $\geqslant 0.45$. Differences in all of the four remaining cross-sectional parameters were also important predictor variables. Because failure to match cross-sectional parameters causes substantial difference in contact variables between an allograft and autograft and because cross-sectional parameters predict the contact pressure on the tibial plateau, protocols used to prospectively select allografts should concentrate on matching cross-sectional parameters and particularly the width to those of the original meniscus. [DOI: 10.1115/1.1503061]

Introduction

Removal of either the entire meniscus or a portion thereof as a method of treatment for non-repairable tears may cause degenerative arthritis in the knee [1–6]. Presumably, the cause of the arthritis is increased contact pressure of the articular cartilage surfaces which increases in direct proportion to the amount of meniscus removed [7]. Therefore, to prevent increased contact pressure and hence the degenerative sequel following removal of a portion of the meniscus, the whole of the tissue is required in the joint. One treatment option that satisfies this requirement is meniscal transplantation. The identification of factors that affect the contact pressure of a meniscal transplant or allograft may enable the selection and surgical implantation of allografts such that allografts function effectively.

Among the factors that affect the contact pressure of a meniscal allograft at the time of implantation are the method of fixation to the surrounding tissues [8,9] and the geometric similarity of the allograft [10,11]. Previous research has isolated the method of fixation as an independent variable for study by comparing the contact pressure of an autograft to that of the intact meniscus. Although the maximum pressure with the autograft is somewhat greater than that for the intact meniscus when physiologic compressive loads are applied to the joint [9,10], the maximum pressure is still significantly lower than that for the meniscectomized knee.

As with the method of fixation, geometrical similarity is also an important factor that must be considered in the selection of allografts by the tissue bank. Tissue banks match donor menisci to recipients by measuring dimensions from either roentgenograms or MR images of the recipient's knee [12]. Dimensions are only measured in the transverse plane however. This procedure assumes that only the transverse geometric features of the menisci and not the cross-sectional geometric features are important determinants of the contact pressure. However, two studies used allografts selected according to this procedure and found that the selection process appears to ignore important geometric features. One study reported an increase in maximum contact pressure for lateral meniscal allografts above that for the normal meniscus

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[11]. In identifying the causes of this pressure increase, obvious gross differences between the cross sections were noted. The authors suggested that more careful geometric matching would improve any biomechanical effect. Another study reported that measures of contact pressure (i.e. maximum pressure, mean pressure, and contact area) were much more variable across the ten specimens tested for an allograft than for an autograft and suggested that differences between the size and shape of the two tissues may explain the increased variability for the allografts [2]. Since the transverse features were controlled to some degree in the selection process whereas the cross-sectional features were not, these studies suggest the need to consider cross-sectional features in selecting donor menisci.

Fifteen cross-sectional parameters have been used to define the cross-sectional features of the lateral meniscus [13]. However, it is unknown which of these parameters are determinants of the contact pressure of the articular surface of the tibia. The purpose of the present study was to identify which cross-sectional parameters of a lateral meniscal allograft predict the contact pressure of the articular surface of the tibia. If the cross-sectional parameters that are the most important determinants of the contact pressure are known, then tissue banks could modify their selection procedures to match these parameters as well as those describing the transverse geometric features.

Because the method of fixation is known to affect the contact pressure at the time of implantation [9] and because a method of fixation must be used for an allograft, an experimental protocol must be used to isolate the effect of the cross-sectional features of the allograft from that of the method of fixation. Such a protocol can be achieved by determining the contact pressure for an autograft and then using this pressure as a baseline for comparison to the contact pressure determined with an allograft [10]. Since both grafts are fixed to the surrounding tissues similarly, the method of fixation and its effect on the contact pressure is removed as a confounding factor from the study.

Materials and Methods

Experiments. Fifteen human, fresh-frozen cadaveric knees were obtained from 6 females and 9 males with an average age of 52 years (age range 23–69 years). Antero-posterior and lateral roentgenograms of each knee were obtained and only specimens without joint space narrowing, osteophytes, chondrocalcinosis, meniscal tears, and prior knee surgery were included in the study.

The recipient knee was sized to select a lateral meniscal allograft by measuring four transverse dimensions from the MRI scans. Measurements were made from MRI scans rather than directly from the knee because the soft tissues obscured the landmarks. The four transverse dimensions that were measured included the medial-lateral width of the tibial plateau, the anterior-posterior depth of the lateral compartment of the tibial plateau (Fig. 1), the anterior-posterior depth of the lateral meniscus (Fig. 2), and the medial-lateral width of the lateral meniscus (Fig. 3).

The allograft menisci were selected from a pool of 22 fresh-frozen tibial plateaus with lateral menisci obtained through four tissue banks (Cryolife, Marietta, GA; IIAM, Scranton, PA; NDRI, Philadelphia, PA; Biopolymers, Tucson, AZ). Of the 22 candidate allografts, 16 were male and 6 were female with an average age of 48 years (age range 21–69 years). Using a scale, the four transverse dimensions were measured directly from the donated tissue to simulate how sizing is performed in a tissue bank [12]. A meniscal allograft was considered to be an acceptable match for a recipient knee when all four transverse dimensions were within 3 mm.

Before testing, each knee was prepared for mechanical alignment in a load application system. Soft tissues within 10 cm of the joint line were left intact and the rest were removed. To interface the specimen with the load application system, steel rods 12.5 mm in diameter were inserted into the medullary canal of the femur and tibia and cemented in place with polymethylmethacrylate (PMMA).

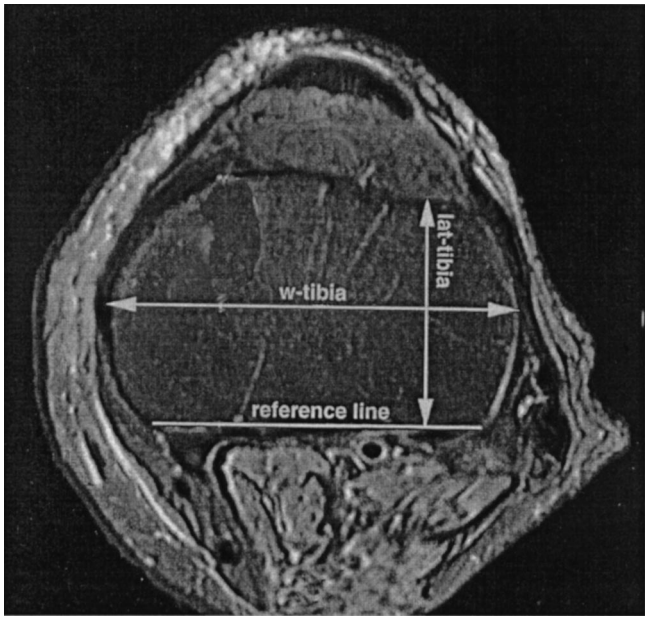

Fig. 1 Example MR image of the tibial plateau in the transverse plane indicating two of the four transverse dimensions measured. A reference line was drawn intersecting the most posterior edge of the tibial plateau on the transverse image closest to the joint line. The width of the tibia was measured parallel to the reference line, and the maximum depth of the lateral compartment of the tibial plateau was measured perpendicular to the reference line.

Each knee was then aligned in the load application system, a joint testing apparatus designed in our laboratory [14]. The knee was aligned using a functional-axes approach, a technique with

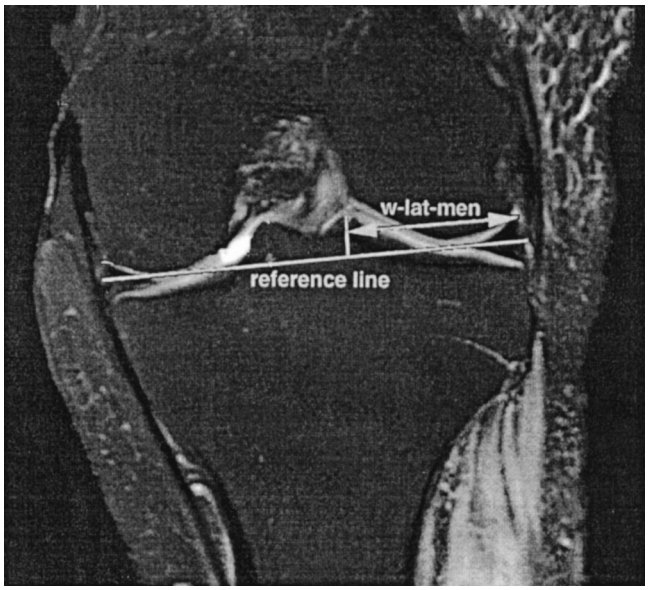

Fig. 2 Example MR image in the sagittal plane indicating one of the four transverse dimensions measured. The depth of the lateral meniscus was measured from the sagittal image that best bisected the lateral compartment. A reference line was drawn through the tibial plateau and the depth of the lateral meniscus was measured parallel to that line.

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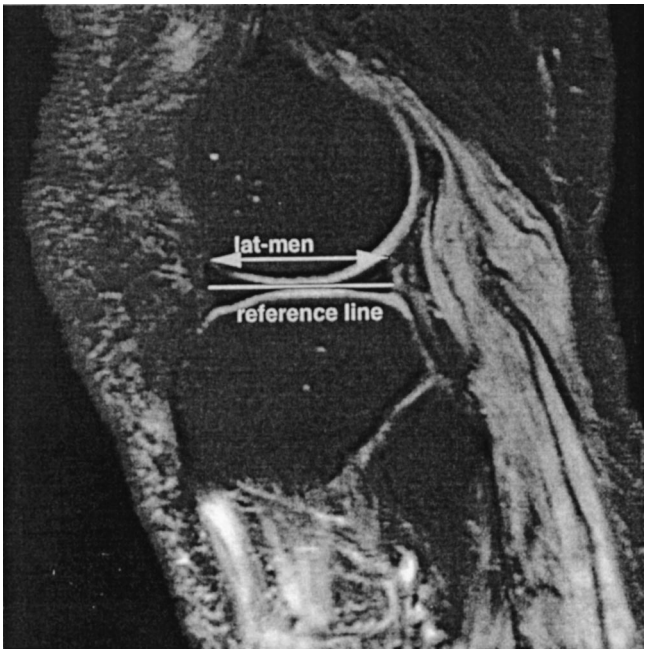

Fig. 3 Example MR image in the coronal plane indicating one of the four transverse dimensions measured. The width of the lateral meniscus was measured parallel to the articular surface of the tibia on the coronal image that best displayed the tibial spines. A reference line was drawn through the tibia and the width of the lateral meniscus was measured from the outer edge of the meniscus to the lateral spine.

good repeatability [15]. After alignment, the specimen was potted into hollow, rectangular tubes using PMMA. These tubes allowed the specimen to be removed and returned to the testing apparatus while maintaining alignment.

After the alignment, the specimen was removed from the testing apparatus and a lateral osteotomy was performed to allow easy removal and implantation of the lateral meniscus as an autograft. The lateral osteotomy was developed from a previously described procedure for a medial osteotomy [16]. Our technique for the lateral osteotomy removed the lateral femoral condyle rather than the medial condyle, and detached less of the condyle than had been detached for the medial osteotomy. Pilot studies showed that a shallower cut into the lateral condyle was necessary to allow the consistent and repeated application of 1200 N loads without splintering of the femur. The fixation techniques used to reassemble the lateral femoral condyle remained the same as in the medial osteotomy.

The lateral meniscus was harvested as an autograft by removing the anterior and posterior horns attached to a bone plug. A 2.4 mm diameter K-wire was drilled through the center of the posterior horn of the meniscus across the tibial metaphysis exiting distally on the antero-medial aspect of the tibia. A second K-wire was drilled through the center of the anterior horn, exiting distally on the postero-lateral aspect of the tibia. The peripheral margin of the meniscus was detached leaving a 1–2 mm rim. A 10 mm cannulated reamer was then drilled from distal to proximal over each guide wire to within 15 mm of the tibial plateau. A cannulated coring reamer, with a 10 mm outside diameter, and an 8 mm inside diameter (Acufex, Waltham, MA), was advanced within the tunnel up to the joint line to form bone plugs 8 mm in diameter and 15 mm in length attached to the horns of the meniscus. To prevent failure of the bone plugs during compressive loading of the joint, the plugs were reinforced with a screw and bone cement as described in a previous study [9]. The allograft was harvested and prepared from the donated tissue in a similar fashion.

Two ranges of pressure sensitive film were used in this study (Super-low and Low pressure film, Fuji Prescale Film; C Itoh, New York, NY) [11,17]. Super-low pressure film, which measures pressures in the rated range of 0.5 to 2.5 MPa, was selected because it provides a more accurate measurement of the contact area than low pressure film. Low pressure film, which measures pressure in the rated range of 2.5 to 10 MPa, was selected because it provides a more accurate measurement of maximum pressure than super-low pressure film [9].

Pressure sensitive film packets were created for each knee to match both the size and shape of the lateral tibial plateau using a previously described technique [9,16]. Briefly a 0.8 mm thick piece of Teflon was trimmed to fit on the articular surface under the lateral meniscus. This template was used to prepare 0.25 mm thick polyethylene film packets for each range of film. All film packets for a specimen were sealed at the same time to standardize the humidity, and the relative humidity in the room was recorded [18].

The order in which the knee with the autograft and the knee with the allograft were tested was randomized. In preparation for measuring the contact pressure, the autograft and allograft were secured to the tibial plateau by cementing the bone plugs into the same bone tunnels drilled when forming the autograft.

The specimen was preconditioned using the load application system. The load application system constrained flexion at a predetermined angle while applying compressive loads. Unconstrained motion was permitted in all other degrees of freedom [14]. The specimen was preconditioned by compressing the knee to 1200 N over a 15-second interval, holding for 5 seconds, and releasing. Three complete loading cycles were applied at both 0 and 45 degrees of flexion.

Following preconditioning, contact pressure of the knee with the graft was measured with the pressure sensitive film as compressive load was applied using the load application system. Four factors were controlled during the exposure of the pressure sensitive film: shear, orientation, overshoot, and loading time [16]. Orientation of the film on the tibial plateau was recorded by placing two dots on the film in regions minimally exposed during loading. The dots were created by inserting two pins through two 1.6 mm diameter tunnels drilled through the tibia and articular surface [19]. Three repetitions were made at each of the four randomized flexion angles of 0, 15, 30, and 45 degrees, at 1200 N. The flexion angles represented the motion of the knee during the stance phase of gait [20]. The load level represented 1 1/2 times body weight.

After all compressive loading was completed, cross-sectional parameters of both the autograft and allograft were determined using measurements derived from a three-dimensional coordinate digitizing system (3-DCDS) and a previously described technique [13,21]. Briefly, the superior surface of the lateral meniscal autograft (secured with bone plugs using PMMA) was scanned using the 3-DCDS. This was repeated for the allograft, and then for the superior surface of the tibial plateau. The scan of the tibial plateau was subtracted from the scan of the superior surface of both the autograft and allograft to yield a set of three-dimensional surface coordinates representing the geometry of the meniscus.

Data Processing. A finite element package (PATRAN, MacNeal-Schwendler Corp., Los Angeles, CA) was used to manipulate the three-dimensional geometric representation of the meniscus to obtain five cross-sectional parameters in each of three regions (anterior, middle, and posterior). Each meniscus was divided into ten sectors with equal arc length by transecting the outer edge of the meniscus at nine locations (Fig. 4*a*). A x_m-z_m reference frame was applied to each transection to acquire the five parameters used to describe the cross section (Fig. 4*b*). The x_m-axis was drawn parallel to the standardied transverse plane through the inner edge of the meniscus. The z_m-axis was drawn through the highest point on the meniscus perpendicular to the x_m-axis. The five parameters that were used to describe the cross section included the width of the meniscus (w_o), the height of the

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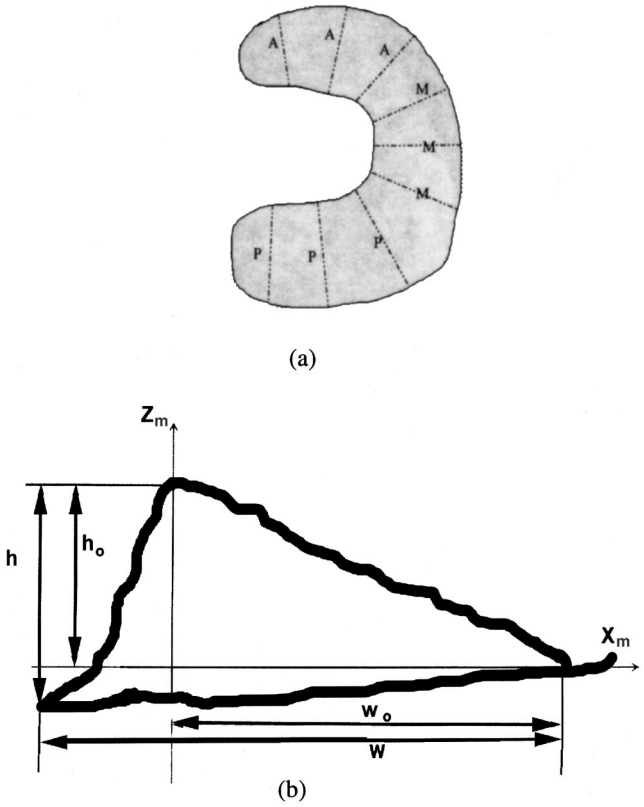

Fig. 4 (*a*) **Schematic of slices made in the lateral meniscus to transect it into 10 sectors grouped into the anterior (A), middle (M), and posterior (P) regions. (*b*) Schematic of cross section and measurements made to determine five cross-sectional parameters. In addition to the three parameters indicated, two other parameters were the height ratio (h/h_o) and the slope (h_o/w_o). Due to requirements of the testing protocol, the maximum width (w) could not be measured.**

meniscus (h_o), the maximum height of the meniscus (h), a height ratio (h/h_o), and the slope (h_o/w_o). To obtain a representative description of the cross section while limiting the number of parameters to a manageable value, each of the five cross-sectional parameters was computed from the average of the three transections within the anterior, middle, and posterior regions [13].

Differences in the cross-sectional parameters of the lateral autograft and allograft were calculated by subtracting the parameter of the allograft (AL) from that of the autograft (AU) [AU−AL]. These differences were computed for a total of 15 cross-sectional parameters. These differences were then used as the predictor variables for the differences in contact variables between the knee with the lateral autograft implanted and the knee with the lateral allograft implanted.

To convert the intensity of the film stain to a pressure value, a series of calibration curves was generated [22]. Because the exposure of the pressure sensitive film is determined not only by the pressure but also by the humidity, the relative humidity was recorded while film packets were being prepared for each specimen. Calibrations were then performed to encompass the range of relative humidities recorded. Calibration curves were generated for three different relative humidity levels (31%, 38%, and 42%). For each relative humidity level, the super-low range film was calibrated over the pressure range of 0.25–4.0 MPa in 0.25 MPa increments. The low range film was calibrated over the pressure range of 2.5–7.0 MPa in 0.25 MPa increments. The calibration loads were applied using a servohydraulic materials testing system (Model 858, MTS, Minneapolis, MN) and a previously described loading setup [23]. The exposed pressure stains were then transformed into color images using a high resolution scanner (Model 4c, Hewlett-Packard Corp, Palo Alto, CA). The color images were converted into 8-bit grayscale images and the average grayscale value was measured using image analysis software (NIH Image, version 3b for Windows NT, Scion Corporation). Finally, a calibration curve relating pressure to grayscale value was derived using a fourth order polynomial regression [18].

Following testing of the cadaveric knees, all of the film packets exposed at a specific joint condition over the four flexion angles were scanned simultaneously for consistency [16]. From the calibrated images, the maximum pressure, contact area, mean pressure, and the local x and y locations of the centroid of the contact area were determined. The x and y coordinates were in a local coordinate system established by placing the origin at the posterior of the two dots marked on the pressure sensitive film and connecting the two dots with a line designated as the x-axis.

The maximum pressure (P_{MAX}) at a flexion angle was determined by averaging the maximum pressure from the three trials using only the low range film (Tables 2 and 3). The difference in maximum pressure between the knee with the allograft and the knee with the autograft was calculated by subtracting the value of the maximum pressure of the knee with the autograft ($P_{MAX,AU}$) from the value of the maximum pressure of the knee with the allograft ($P_{MAX,AL}$) [$P_{MAX,AL}-P_{MAX,AU}$] (Table 4).

The total contact area (A) at a flexion angle was determined by averaging the contact area from the three trials using only the super-low range film (Tables 2 and 3). The difference in the contact area between the knee with the allograft and the knee with the autograft was calculated in the same manner as with the maximum pressure (Table 4).

The mean pressure (P) for a trial was obtained from both the super-low and low range films. For each trial, the contact area (A_L) and mean pressure (P_L) were determined for the low range film. From the super-low range film, the contact pressure for the

Table 1 Means and standard deviations of cross-sectional parameters measured in each of the three regions for both the autograft and the allograft. The root mean squared difference (RMSD) between an allograft parameter and the corresponding autograft parameter and this difference as a percent of the autograft parameter are also given.

		h (mm)	h_o (mm)	h/h_o	w_o (mm)	h_o/w_o
Autograft	Anterior	6.46±1.93	3.86±1.14	1.77±0.52	9.60±1.52	0.40±0.10
	Middle	6.86±2.27	4.49±1.71	1.67±0.65	9.81±1.49	0.45±0.14
	Posterior	8.29±2.08	5.18±2.94	1.92±0.62	10.21±1.87	0.42±0.26
Allograft	Anterior	6.63±1.99	4.14±1.81	1.86±0.93	9.92±4.11	0.42±0.14
	Middle	7.43±3.20	4.70±2.52	1.75±0.53	10.18±2.93	0.48±0.29
	Posterior	8.12±2.40	3.35±1.29	2.72±1.16	9.77±3.48	0.37±0.16
RMSD	Anterior	2.29 (37.5%)	1.72 (47.2%)	0.59 (30.5%)	3.77 (35.3%)	0.13 (33.7%)
	Middle	4.05 (75.8%)	3.18 (100.4%)	0.77 (38.5%)	2.80 (28.3%)	0.33 (116.3%)
	Posterior	3.35 (40.7%)	3.91 (571.8%)	8.54 (110.3%)	3.60 (30.6%)	0.35 (386.9%)

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Table 2 Means and standard deviations of contact variables for the autograft

	0°	15°	30°	45°	Pooled
Max Pressure (MPa)	7.37±2.41	6.68±2.51	6.04±2.29	6.50±2.24	6.65±2.21
Mean Pressure (MPa)	3.79±1.67	3.27±0.86	3.04±1.01	3.25±1.07	3.34±1.18
Contact Area (mm^2)	231.0±56.4	250.0±66.6	238.6±64.0	223.7±67.9	235.8±62.9
X Coordinate (mm)	0	0	0	0	0
Y Coordinate (mm)	0	0	0	0	0

Table 3 Means and standard deviations of contact variables for the allograft

	0°	15°	30°	45°	Pooled
Max Pressure (MPa)	7.32±1.96	7.20±1.95	6.82±2.22	6.66±2.19	7.00±2.05
Mean Pressure (MPa)	3.76±1.37	3.44±1.05	3.20±1.15	3.15±0.96	3.39±1.13
Contact Area (mm^2)	217.9±68.9	225.9±53.3	216.2±62.4	224.2±88.6	221.0±65.5
X Coordinate (mm)	−4.8±5.4	−3.6±2.6	−3.5±2.9	−4.0±0.9	−4.0±3.6
Y Coordinate (mm)	1.6±3.0	0.4±0.9	0.6±1.2	0.99±2.0	0.99±1.9

Table 4 Root mean square difference (RMSD) between values of the contact variables for an autograft and the contact variables for the corresponding allograft and this difference as a percent relative to the contact variables for the autograft.

	0°	15°	30°	45°	Pooled
Max Pressure (MPa)	1.97 (30.3%)	1.27 (33.4%)	1.16 (27.5%)	1.00 (24.3%)	1.41 (29.0%)
Mean Pressure (MPa)	0.55 (25.1%)	0.43 (15.7%)	0.41 (14.4%)	0.56 (18.3%)	0.49 (18.9%)
Contact Area (mm^2)	41.89 (19.2%)	48.00 (16.2%)	61.65 (20.0%)	72.9 (34.1%)	57.4 (23.6%)
X Coordinate* (mm)	5.1	1.98	3.3	3.2	3.6
Y Coordinate* (mm)	4.1	2.4	2.0	4.0	3.3

*Note that no percentage difference is given because the X and Y coordinates of the centroid of pressure for the autograft were arbitrarily set equal to 0.

Table 5 R-squared values of the regression models ($p \leq 0.05$) in which differences in cross-sectional parameters predict differences in the contact variables of the knee. Bolded values are considered to be reasonably predictive because the R-squared values are greater than 0.45. In the regression models where more than one predictor variable was entered, the variable at the top was the most important.

Angle	0°	15°	30°	45°	Differences between Autograft and Allograft
Variables	$w_{0,a}$	$h_0/w_{0,p}$	$h_{0,p}$	none	**Contact Area**
R^2	**0.713**	**0.473**	0.326		
R_a^2	**0.690**	**0.425**	0.265		
Variables	none	none	$w_{0,m}$	none	**Mean Pressure**
R^2			0.310		
R_a^2			0.225		
Variables	$w_{0,p}$	none	$h_{0,m}$	$h/h_{0,p}$	**Max Pressure**
R^2	**0.498**		**0.635**	**0.613**	
R_a^2	**0.456**		**0.602**	**0.581**	
Variables	$h_0/w_{0,a}$	$h_{0,a}$	$h_{0,p}$ $h_{,m}$	$h_0/w_{0,a}$	**Anatomic X-location of Centroid of Area**
R^2	0.161	0.314	**0.813**	0.164	
R_a^2	0.085	0.252	**0.776**	0.086	
Variables	$h_0/w_{0,m}$ $h_{,m}$ $w_{0,m}$	$w_{0,p}$ $w_{0,a}$	$w_{0,p}$ $h/h_{0,p}$	$h_0/w_{0,m}$ $h/h_{0,p}$	**Anatomic Y-location of Centroid of Area**
R^2	**0.583**	**0.468**	**0.618**	0.364	
R_a^2	**0.444**	**0.361**	**0.542**	0.237	

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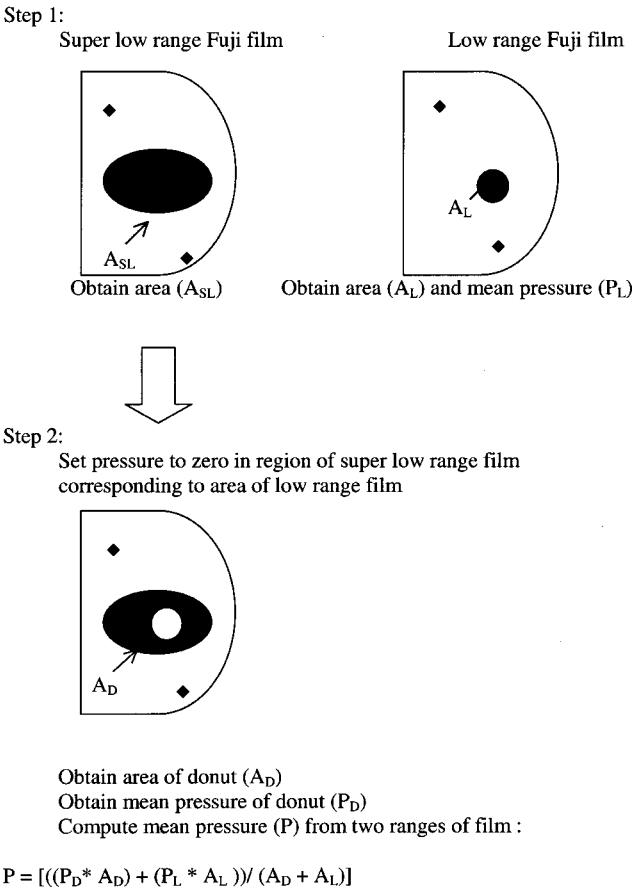
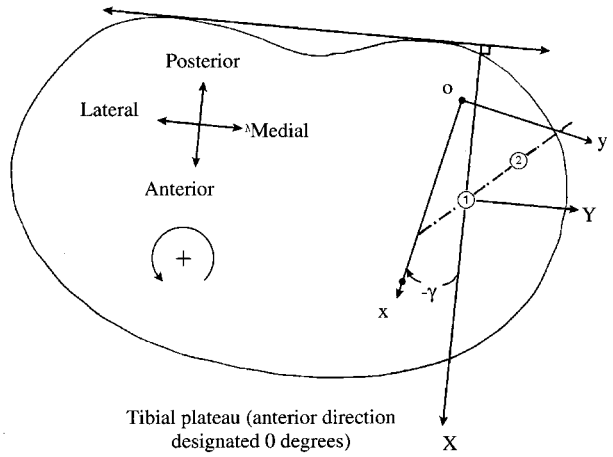


Fig. 5 The technique used to calculate the mean pressure from two ranges of pressure sensitive film.



Anatomic X (i.e. AP) axis is obtained from PATRAN based on bony landmarks

- o = origin of local coordinate system
- x = x axis of the local coordinate system
- y = y axis of the local coordinate system
- 1 = Location of centroid of area with the autograft (x_1, y_1) and origin of anatomic coordinate system.
- 2 = Location of centroid of area with the allograft (x_2, y_2)
- γ = Angle of x-axis of local coordinate system from the anatomic X-axis obtained from PATRAN

Fig. 6 Diagram illustrating the procedure for determining the difference in the locations of the centroid of area between the autograft and the allograft in the anatomic coordinate system.

region corresponding to that of the low range film was first set to zero. Then the mean pressure (P_D) and the contact area (A_D) of the remaining donut-shaped region of interest were calculated (Fig. 5). The mean pressure (P) for the composite image was calculated from

$$P=[((P_D*A_D)+(P_L*A_L))/(A_L+A_D)] \quad (1)$$

The mean pressure at a flexion angle was determined by averaging the mean pressure from the three trials (Tables 2 and 3). The difference in mean pressure between the knee with the allograft and the knee with the autograft was calculated in the same manner as with the maximum pressure (Table 4).

The shifts in the X and Y locations of the centroid of the contact area in an anatomic coordinate system were determined in four steps. In the first step, the local x and y coordinates of the centroid of the contact area at a flexion angle were determined by averaging the local coordinates from the three trials using only the super-low range film. Then the vector from the centroid of area with the autograft to the centroid with the allograft was determined in the local coordinate system. In the second step, an anatomic coordinate system was established using PATRAN. The X-axis defining the anterior(+)/posterior(−) direction was determined by drawing a line perpendicular to a line connecting the posterior osteochondral junctions of the medial and lateral compartments of the tibial plateau (Fig. 6). The origin of the anatomic coordinate system was the location of the centroid of area with the autograft (Table 2). The Y-axis defining the medial (+)/lateral (−) direction was parallel to the line connecting the posterior osteochondral junctions of the medial and lateral compartments of the tibial plateau. In the third step, an angle (γ) formed between the local x-axis (i.e. line connecting the holes drilled to establish the local coordinate system) and the anatomic X-axis was measured. In the final step, the vector connecting the two area centroids in the local coordinate system was transformed to the anatomic coordinate system using the angle γ (Tables 2 and 3).

Statistical analyses were performed using the SAS software package (Cary, NC). A forward stepwise regression (significance at 0.05) was used initially to serve as a screening procedure to identify the number of variables to be included in the model which was limited to at most three. In the regression analyses, the total number of predictor variables included the differences in the 15 cross-sectional parameters. However, both because stepwise regression models include only linear terms and because this approach identifies only one subset of predictor variables whereas other subsets may be "good" as well, the stepwise regression was followed by an all-possible-subsets procedure using the number of predictor variables indicated in the stepwise regression model [24]. The quality of the models was assessed by calculating both R^2 and adjusted R^2 values. Additional predictor variables were included in the model if the adjusted R^2 value of the model with the additional variable was greater than the adjusted R^2 of the model without that particular variable. A cross-sectional parameter difference with a $R^2 \geqslant 0.45$ was considered to be predictive of the differences in contact variables of the knee.

Because all of the regressions for screening purposes assumed that the model form was linear with no interactions, this assumption was checked for the best three models. To perform this check, both a second order term (i.e. quadratic) and an interaction term were included for each of the variable pairs in all three models. If either non-linearity or interaction was evident quantitatively, then the form of the model was adjusted accordingly and the regressions repeated with the adjusted model form.

Diagnostic analyses were performed on the best model(s) to insure its propriety. Diagnostic tests included the creation of residual plots to qualitatively check the relation between the predictor and response variables, the equal variance assumption, and the normality of the error term. Also to insure that any multicollinear-

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ity did not affect results, variance inflation factors were computed for each of the coefficients. A maximum value of 10 was taken as evidence that significant multicollinearity influenced the results. None of these diagnostics revealed that any remedial measures were necessary.

Results

Although there was little difference between the geometric parameters describing the autograft and those describing the allograft on average (Table 1), when each allograft was paired with the corresponding autograft the differences between matched pairs were substantial. Referenced to the autograft, the root mean squared differences ranged from a minimum of 28% for the width of the posterior region ($w_{o,p}$) to 572% for the height of the posterior region ($h_{o,p}$).

Likewise, the differences between the contact variables were substantial when the contact variables for each allograft were paired with those for the corresponding autograft. Referenced to the autograft, the root mean squared differences taken over all four flexion angles were 29% for the maximum pressure, 19% for the mean pressure, and 24% for the contact area. These differences indicate that the allografts did not provide contact pressure distributions that closely matched those of the autografts.

The cross-sectional parameter difference that was included most often in the regression models that predicted differences in contact variables with $R^2 > 0.45$ (Table 4) was the difference in the widths. The difference in width was a predictor variable in five of the nine models. The difference in the widths of the posterior region ($w_{o,p}$) predicted the difference in maximum pressure at 0 degrees of flexion ($R^2 = 0.498$) and was also included in the regression models that predicted the difference in the Y-location of the centroid of area at both 15 degrees ($R^2 = 0.468$) and 30 degrees ($R^2 = 0.618$). The difference in widths of the anterior region ($w_{o,a}$) predicted both the difference in contact area at 0 degrees of flexion ($R^2 = 0.713$) and was included in the regression model that predicted the difference in the Y-location of the centroid of area at 15 degrees flexion ($R^2 = 0.468$). Finally, the difference in widths of the middle region ($w_{o,m}$) was one of three variables included in the model that predicted the difference in the Y-location of the centroid of contact area at 0 degrees ($R^2 = 0.583$).

The difference in height was a predictor variable in two of the nine regression models with $R^2 > 0.45$ (Table 4). The differences in height of the middle region ($h_{o,m}$) predicted the difference in the maximum pressure at 30 degrees ($R^2 = 0.635$). The difference in height of the posterior region ($h_{o,p}$) was one of the two predictor variables included in the regression model that predicted the difference in the anatomic X-location of the area centroid at 30 degrees of flexion ($R^2 = 0.813$).

The difference in height ratios was a predictor variable in two of the nine regression models with $R^2 > 0.45$ (Table 4). The differences in height ratios of the posterior region ($h/h_{o,p}$) predicted the difference in maximum pressure at 45 degrees of flexion ($R^2 = 0.613$) and was one of two predictor variables in the model that predicted the difference in the Y-location of the centroid at 30 degrees flexion ($R^2 = 0.618$).

The difference in the maximum height was a predictor variable in two of the nine regression models with $R^2 > 0.45$ (Table 4). The difference in maximum height of the middle region ($h_{,m}$) was included in the regression models that predicted the differences in both the X-location of the centroid of area at 30 degrees ($R^2 = 0.813$) and the Y-location of the centroid of area at 0 degrees ($R^2 = 0.583$).

Finally, the difference in the slope was a predictor variable in two of the nine regression models with $R^2 > 0.45$ (Table 4). The difference in slope in the posterior region ($h_o/w_{o,p}$) was included in the regression model that predicted the difference in the contact area at 15 degrees ($R^2 = 0.473$) and was one of three predictor variables included in the regression model that predicted the difference in the anatomic Y-location of the area centroid at 0 degrees of flexion ($R^2 = 0.583$).

Discussion

The purpose of this study was to identify which cross-sectional parameters of a lateral meniscal allograft predict the contact variables of the articular surface of the tibia. The key findings were that 1) the parameters chosen to characterize the cross section of the meniscus varied widely, 2) the contact pressure distributions for an allograft differed substantially from those of the paired autograft, and 3) differences in all of the five parameters describing the cross section in each region accounted for differences in the contact variables over the range of flexion studied. Before discussing the importance of these findings, several methodologic issues should be reviewed.

Methodologic Issues. A discussion of the limitations associated with using pressure-sensitive film, the method of inserting, exposing, and removing the film from the knee, use of elderly knee specimens, and the load-application system for measuring contact pressure on the tibial plateau has been detailed previously [9,16]. The consensus reached in these reports, and which also apply to this study, was that any limitations imposed by these sources did not affect the conclusions from the study.

Lateral meniscal allografts were selected based on the four transverse dimensions of the tibial plateau and lateral meniscus. Originally, our intention was to use the same selection protocol as the tissue bank (Cryolife, Inc., Marietta, GA). The specifics of their protocol were proprietary and hence unavailable to us however, so that a new selection protocol was devised. The four transverse dimensions chosen for our selection protocol included two transverse dimensions of the tibial plateau and one transverse dimension of the lateral meniscus similar to the tissue bank's selection protocol. Additionally, one transverse dimension of the lateral meniscus that was not part of the measurements routinely obtained by the tissue bank was measured because of a strong correlation between meniscal and bony dimensions [25]. Accordingly, our results may not be directly applicable to the tissue bank's proprietary methods of allograft selection.

In an attempt to isolate the cross-sectional parameters as the independent variables for study, the transverse dimensions were controlled in the selection of meniscal allografts. The 3-mm tolerance was based on an accepted tolerance of 5% between donor and recipient knees [26]. Given the dimensions of the tibial plateau, the 3-mm absolute tolerance gave approximately a 5% relative tolerance. However, it was unknown at the outset of the experiment whether this tolerance was sufficient to render differences in transverse dimensions unimportant as determinants of differences in contact variables. Thus the differences of the transverse dimensions were also investigated as predictor variables. Only the difference in the anterior-posterior depth of the lateral compartment of the tibial plateau predicted the difference in mean pressure at 45 degrees of flexion ($R^2 = 0.600$). The fact that the differences in the transverse dimensions were not important predictor variables confirms that the 3-mm tolerance rendered the transverse parameters unimportant as determinants of the contact pressure.

In evaluating how well the differences in cross-sectional parameters predicted the differences in contact variables in the regression analysis, an $R^2 > 0.45$ was selected. After inspection of the regression plots for various R^2 values and noting that all values above 0.45 were significant to $p < 0.05$, R^2 values greater than 0.45 were considered to be reasonably predictive. However, it is unknown what degree of prediction is necessary to improve contact pressure with a meniscal allograft.

An assumption implicit to using differences in the cross-sectional parameters as predictor variables was that differences in the material properties between the intact meniscus and the al-

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lograft would not affect the results of the study. Mathematical models that have examined the role of the meniscus in the load transmission of the tibio-femoral joint confirm that material properties such as the circumferential tensile modulus is an important property [27,28]. Because of the importance of the circumferential tensile modulus and because of the variation in this property between specimens [29], it is possible that any differences in material properties affected the differences in the measured contact variables within a specimen. However, material property differences were a random effect over all of the specimens. As such, this effect would have inflated the variability between specimens. Despite this inflation, a number of differences in cross-sectional parameters were predictive of differences in contact variables as evidenced by R-squared values greater than 0.45 for the regression analyses (Table 4). Accordingly, the cross-sectional geometry effect was sufficiently strong so that predictive relations from the regression analyses were still obtained.

In performing the lateral osteotomy to expose the lateral compartment of the knee so that the autograft could be harvested, it was assumed that the procedure did not affect the contact pressure on the lateral tibial plateau. This assumption was based on a previous study that validated the medial osteotomy as a benign procedure having virtually no measurable effect ($<1\%$) on the five contact variables measured in the present study [16]. Inasmuch as the two procedures were identical with the exception of the shallower cut in the lateral femoral condyle, it is reasonable to assume that the lateral osteotomy performed similarly to the medial osteotomy in presenting no measurable effect on tibio-femoral contact pressure in the lateral compartment.

Although the osteotomy did not affect measurement of contact pressure, it did limit the level of compressive loading that could be applied to the knee without risk of structural failure of the femur. Ideally, the applied compressive load should have been about 1500 N (i.e. 2 times body weight) to approximate the load across the knee during walking [30]. Although meniscal allografts from donors less than 48 years of age can tolerate a compressive load of 1800 N [11], pilot studies revealed that the osteotomy could not consistently support loads substantially greater than 1200 N (i.e., 1 1/2 times body weight). Even though a load of 1200 N was somewhat lower than ideal, this load was sufficient to cause differences in contact variables between joint conditions. Thus the 1200 N load was appropriate for the purposes of this study.

Although ideally the five parameters used to describe the cross section would have been the same five parameters used by Haut et al. [13], the testing protocol required that the five cross-sectional parameters used in this study be different than those defined by Haut et al. [13]. Imaging the meniscus with the 3-DCDS to determine the cross-sectional parameters required disarticulation of the knee. Accordingly, the cross-sectional parameters were not measured until after the autograft and allograft were harvested and then tested under compressive loading. In harvesting the meniscal grafts, the three bulge parameters and the three maximum width parameters of the menisci defined by Haut et al. were necessarily lost because this procedure required that the peripheral 1-2 mm of the meniscus which forms the bulge remain on the tibial plateau. Instead, the widths of the three regions of the meniscus were added to replace the maximum widths in the parameter set defined by Haut et al. [13] and the heights were added after observing that the slope and height ratio predicted the contact variables in some preliminary regressions.

Importance and Interpretation of Results

The most important finding of this study was that differences in all of the five parameters describing the cross-sectional geometry in each region accounted for differences in the contact variables. Differences in the width were included as predictor variables in more regression models (i.e. five of nine) that related cross-sectional parameters to differences in contact variables with $R^2 > 0.45$ than any other parameter. All three regions were included in these five models (Table 4). Secondary to the differences in the width, differences in all of the four remaining cross-sectional parameters were also included in regression models (i.e. two of the nine for each remaining parameter) but with less frequency than differences in width.

The important role of the width in determining the contact pressure distribution is well recognized. Previous studies on the load-bearing role of the meniscus have demonstrated that the intact meniscus transmits the majority of the compressive force [31,32]. When a portion of the meniscus is removed, the contact stress increases in proportion to the amount of meniscus removed [7]. From these studies it can be inferred that the width of the meniscus is an important determinant of the contact pressure distribution. This is not surprising since the meniscus provides conformity with the femoral condyles. Accordingly decreasing the degree of conformity by removal of a portion of the meniscus would be expected intuitively to increase the contact pressure.

Although the important role of the width has been well recognized and the results of the present study confirm this importance, the present study adds the extra result that the width of the meniscus within the normal limits of variation is an important determinant of the contact pressure distribution. As measured in this study, the average width of the lateral meniscus was approximately 10 mm independent of the region of interest (Table 1) and the range was typically about ± 3 mm. With such a range and no control of the parameters describing the cross section, an intact meniscus with a width of 13 mm could be replaced by an allograft that is only about half as wide. Because this difference in the width of 6 mm could easily correspond to the amount of the width removed during a partial meniscectomy, failure to match the width of a meniscal allograft to that of the original meniscus prior to surgical replacement could lead to a knee where the replacement meniscus functions comparably to a meniscus which has been partially excised.

Another new finding from this study is that the height is also an important determinant of the contact pressure distribution. As with the width, the height (h_o) and the maximum height (h) also varied widely between the menisci (Table 1). Over all three regions the average maximum height was about 7.3 mm while the average height was about 4.2 mm. The ranges were approximately ± 4.3 mm and ± 3.7 mm for the maximum height and height respectively. In the worst case, a meniscus with either a maximum height of 11.6 mm or a height of 7.9 mm could be replaced by an allograft with a maximum height of only 3.0 mm or a height of only 1.5 mm. Inasmuch as the height also affects the conformity of the meniscus with the condyles of the femur, variations of this magnitude could be expected to substantially affect the conformity and hence the contact pressure distribution.

Considering the importance of the cross-sectional parameters in determining the contact pressure distribution on the tibial plateau, the wide variability inherent in these parameters, and the arbitrary selection of the allografts regarding the cross-sectional geometry (i.e. no matching to any cross-sectional parameters including the width), it is not surprising that the contact pressure distributions of the allografts varied widely from those of the autografts (Table 4). For example, for some specimens the maximum pressure for the allograft exceeded that of the autograft by more than 3 MPa. Considering that these increases occurred for specimens where the maximum pressure for the autograft was about 3.7 MPa, relative maximum increases greater than 80 percent were evident. Because maximum pressure increases of this magnitude approach those increases of the meniscectomized knee [11], the clinical implications of such increases are ominous.

High variability in the performance of meniscal allografts selected without matching parameters describing the cross section of the intact meniscus has also been documented for the medial meniscus [10]. In that study, selected specimens demonstrated substantially lower, equal, and substantially higher mean pressures

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with allografts than the pressures determined for the autograft. This result together with the findings of the present study lead to the conclusion that the cross-sectional parameters of the allograft should be matched to some degree to those of the intact meniscus if the contact pressure distribution for an allograft is to consistently approximate that of the autograft.

Following the conclusion that the cross-sectional parameters of an allograft should be matched to some degree to those of the intact meniscus, a further issue becomes the degree of match necessary for each parameter or the tolerances on each parameter. This issue was not addressed in the present study. To address this issue, an approach would be required where each of the geometric parameters is varied in turn while the contact pressure distribution is determined and compared to that for the autograft. This comparison could be used to determine the tolerances on each parameter such that the contact pressure distribution varies from that of the autograft to within some reasonable limits. Determining the tolerances on geometric parameters will be important to developing a procedure that the tissue bank can use to match cross-sectional geometric parameters in the selection of allograft menisci.

Inasmuch as the contact pressure distribution has been measured previously for both lateral meniscal autografts [8] and allografts [11], a comparison with the contact variables determined previously is of interest. However, a meaningful comparison is difficult because the load levels were not the same as the 1200 N load used in the present study; Chen et al. [8] used 400 N whereas the load level used by Paletta et al. [11] was 1800 N. Nevertheless, some observations can be made. Notwithstanding the lower load level of the present study than that of Paletta et al. [11], the maximum pressures determined by Paletta et al. [11] for the allografts were only about half of the maximum pressures measured in the present study (Table 3). This discrepancy may be related to the methods used to determine the maximum pressures. Paletta et al. [11] determined pressures at six arbitrary points on the tibial plateau whereas the present study determined the maximum pressure considering all points on the tibial plateau. Because the location of the maximum pressure would not be expected to consistently coincide with an arbitrary point for different flexion angles and specimens, the maximum pressure reported in the present study is the more representative value.

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