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Use of Roentgenography and Magnetic Resonance Imaging to Predict Meniscal Geometry Determined with a Three-dimensional Coordinate Digitizing System

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Summary: To evaluate and improve on the procedures used by a tissue bank in selecting donor menisci for transplantation, this study was designed to fulfill four objectives: (a) define and quantify a set of independent parameters for describing the geometry of the medial and lateral menisci, (b) determine how well the sizing protocol of the tissue bank (i.e., two transverse roentgenographic measurements obtained from the injured knee or six transverse magnetic resonance imaging measurements obtained from the contralateral knee) predicts the four standard transverse parameters of the menisci, (c) determine if including one additional transverse roentgenographic measurement for each compartment improves the ability of roentgenograms to predict transverse meniscal parameters, and (d) determine if five magnetic resonance imaging measurements at three different meniscal cross sections of the contralateral knee predict the 15 standard cross-sectional parameters of the meniscus in the injured knee. A laser-based, noncontacting three-dimensional coordinate digitizing system was used to determine surface coordinates from which menisci were reconstructed in a computer. For each reconstructed meniscus, four parameters in the transverse plane and five cross-sectional parameters in each of three regions (i.e., anterior, middle, and posterior) were defined, yielding a set of 19 standard parameters to describe the geometry. Through a correlation analysis, these standard parameters were shown to be largely unrelated to one another, thus confirming that the parameters form an independent set describing the three-dimensional geometry of the menisci. The two roentgenographic measurements were poor predictors of transverse standard meniscal parameters, predicting only one of four standard parameters for the medial meniscus and none of four standard parameters for the lateral meniscus with coefficients of determination greater than or equal to 0.5. Including one additional roentgenographic measurement to the tissue bank protocol increased the number of standard transverse parameters predicted to three of four for the medial meniscus and two of four for the lateral meniscus. Magnetic resonance imaging was better than roentgenography for predicting the three-dimensional meniscal geometry. The transverse measurements from magnetic resonance imaging predicted three of four standard transverse parameters for the medial meniscus and all four for the lateral meniscus. With the addition of the cross-sectional measurements by magnetic resonance imaging, seven of 15 standard cross-sectional parameters were predicted for both the medial and lateral menisci. Assuming that a successful clinical outcome depends on how well an allograft matches the size and shape of the original meniscus, magnetic resonance imaging rather than roentgenography should be used for allograft size-matching by tissue banks.

Because removal of a meniscal tear is the most commonly performed procedure in the knee and often results in progressive degeneration of the articular cartilage (4,18), meniscal transplantation is being evaluated as a means to prevent degenerative arthritis by attempting to restore normal contact mechanics to the joint. The geometry of the articulating surfaces of the meniscus has been shown to be an important determinant of the stresses and strains within the tissue during function (3,13,21,23). Therefore, it is reasonable to conclude that meniscal geometry is also an important determinant of contact mechanics (14). If normal contact mechanics are to be successfully restored by a meniscal transplant, then the geometric match between the transplant and the original meniscus must be considered in the transplant selection procedures.

To develop a method for accurately sizing a meniscal allograft so that it matches the three-dimensional geometry (i.e., size and shape) of the recipient's original meniscus, the geometry of the meniscus must first be described accurately. Therefore, there is a need to first define the geometry of the menisci by a set of standard parameters. Possible methods for selecting meniscal allografts can then be evaluated on the basis of their ability to predict the true geometry of the meniscus as defined by these parameters. Considering that no previous study known to the authors has ad-

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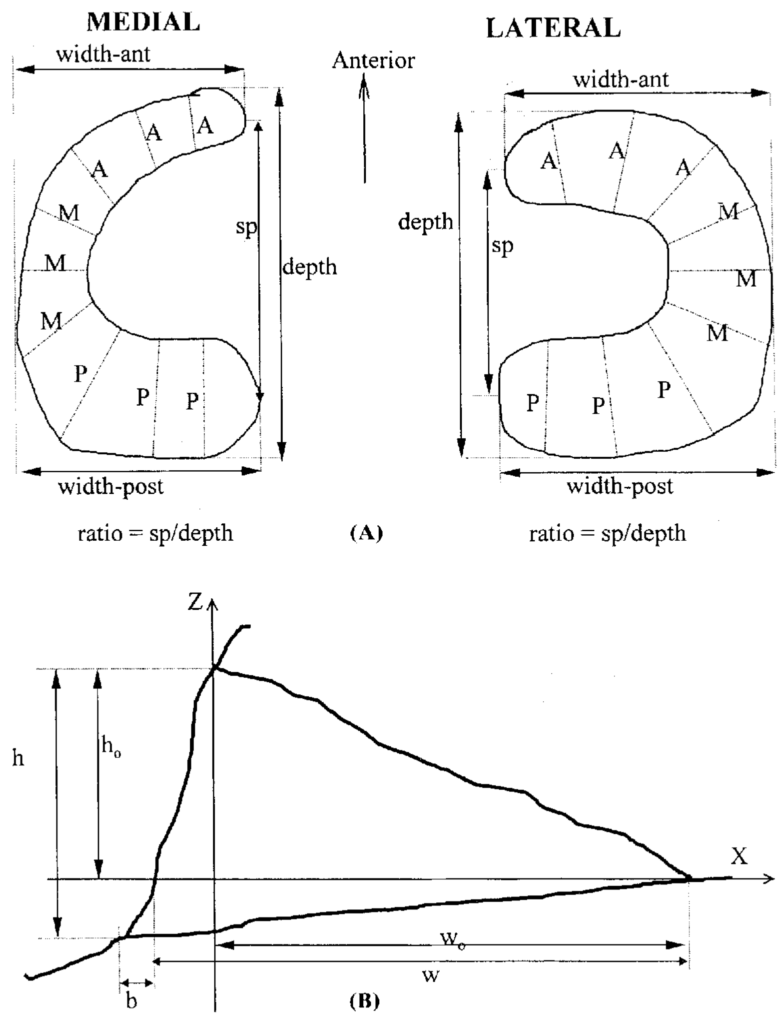

FIG. 1. Schematic illustration of transverse and cross-sectional planes of the human menisci. **A:** Representation of the medial (left) and lateral (right) menisci showing the four transverse parameters with the anterior (A), middle (M), and posterior (P) regions. sp = distance between anterior and posterior horns. **B:** Cross-sectional view of the meniscus showing the five measurements made to calculate the five cross-sectional parameters. h = maximum height of the meniscus measured as the distance from the highest to lowest point on the meniscus along the z axis, h_o = height of the meniscus measured as the distance from the x axis to the highest point on the meniscus along the z axis, b = peripheral bulge measured as the distance from the outer edge of the meniscus on the x axis to the most inferior point on the meniscus measured along the x axis, w = maximum width of the meniscus measured as the distance from the outer to the inner edge of the meniscus along the x axis, and w_o = width of the meniscus measured as the distance from the z axis to the inner edge of the meniscus along the x axis.

dressed this need, one objective of this study was to determine an independent set of standard parameters for describing meniscal geometry with a newly developed laser-based three-dimensional coordinate digitizing system (3-DCDS) (8).

Providing a meniscal allograft that matches the size and shape of the meniscus from the recipient's knee is the responsibility of the tissue bank. Presently, the procedure used to provide the graft is based on a set of proprietary regression equations (Cryolife, Atlanta, GA, U.S.A.) that relate transverse dimensions of the tibial plateau to transverse dimensions of the meniscus. To provide input data to these equations, measurements are made in the transverse plane from roentgenograms of the recipient's meniscectomized knee (10,16,25) or from magnetic resonance imaging (MRI) of the contralateral normal knee (24,25). However, this procedure has not been evaluated for its ability to provide a donor tissue that matches the true transverse geometry of the original meniscus. Thus, the second objective of this study was to determine how well the sizing procedure of the tissue bank (i.e., two transverse roentgenographic measurements obtained from the injured knee or six transverse MRI measurements obtained from the contralateral knee) predicts standard transverse parameters of the medial and lateral menisci. The third objective was to determine if including one additional transverse roentgenographic measurement per compartment (16) improved the ability of roentgenograms to predict standard transverse meniscal parameters.

The merits of considering the cross-sectional size and shape in the selection procedure of the tissue bank have been emphasized in two studies that compared the contact mechanics of a meniscal allograft with those of the normal meniscus (1,15). In each study, the allograft was selected using the tissue bank's procedure with roentgenographic measurements as previously described. In the lateral compartment, the maximum contact pressure for the allograft was found to be significantly above normal (15). Because obvious gross differences in the allograft geometry compared with the normal meniscus were observed, the authors speculated that more careful shape-matching might improve the biomechanical effect from meniscal transplantation. In the medial compartment, the contact mechanics (i.e., maximum pressure, mean pressure, and contact area) were much more variable across the 10 specimens tested for the allograft than for the autograft (1). Inasmuch as the sizing procedure considers only the transverse meniscal dimensions and not the cross-sectional dimensions, taken together these studies suggest that the cross-sectional dimensions are an important determinant of the contact mechanics. Therefore, the final objective was to determine if additional measurements of meniscal cross-sectional geometry measured from MRI were able to predict the standard meniscal cross-sectional parameters.

MATERIALS AND METHODS

Experiments

Ten pairs of fresh-frozen human cadaveric knees free from degenerative arthritis, chondrocalcinosis, and meniscal tears were used. Prospective specimen pairs were evaluated with roentgenography and MRI before inclusion in the study. Images were made with the knee joint fully extended. If either knee in a pair demonstrated any of these conditions, then the pair was excluded from the study. The specimens were obtained from four men and six women with an average age of 65 years (range: 37-78 years). The same images were subsequently used for bone and meniscal measurements.

After the left or right knee from each pair had been randomly chosen, a laser-based, noncontacting 3-DCDS was used to acquire the three-dimensional geometry of the medial and lateral menisci with an error of 15 μm (8). A computer representation of each meniscus was created by measuring the surface contours of the menisci and tibial plateau and then subtracting the surface contour of the tibial plateau measured with the menisci excised. With use of the computer representation, a standardized transverse plane was determined for each tibia by performing a least-squares regression on the data points of the tibial plateau scanned without the menisci. Anterior was defined by a line drawn perpendicular to a line joining the posterior osteochondral junction of the medial and lateral compartments.

Four transverse parameters for each of the medial and lateral menisci were described by four dimensions acquired in the standardized transverse plane (Fig. 1A). The four parameters were the depth (depth), the ratio of enclosure (ratio), the maximum width of the anterior half of the meniscus (width-ant), and the maximum width of the posterior half of the meniscus (width-post).

The cross-sectional geometry of the body of each meniscus was defined by five parameters in each of three regions. Each meniscus was divided into 10 sectors with equal arc length by transecting the outer edge of the meniscus at nine locations (Fig. 1A). An x-z reference frame was applied to each transection to acquire the five parameters used to describe the cross-sectional geometry (Fig. 1B). The x axis was drawn parallel to the standardized transverse plane through the inner edge of the meniscus. The z axis was drawn through the highest point on the meniscus perpendicular to the x axis. From this reference frame, five cross-sectional measurements were made: (a) the width of the meniscus (w_o) measured as the distance from the z axis to the inner edge of the meniscus along the x axis, (b) the maximum width of the meniscus (w) measured as the distance from the outer to the inner edge of the meniscus along the x axis, (c) the height of the meniscus (h_o) measured as the distance from the x axis to the highest point on the meniscus along the z axis, (d) the maximum height of the meniscus (h) measured as the distance from the highest to lowest point on the meniscus along the z axis, and (e) the peripheral bulge (b) measured as the distance from the outer edge of the meniscus on the x axis to the most inferior point on the meniscus measured along the x axis. The five parameters that were used to describe the cross-sectional geometry of the meniscus included the maximum width of the meniscus (w), the maximum height of the meniscus (h), the peripheral bulge (b), a height ratio (h/h_o), and the slope (h_o/w_o). To obtain a representative cross-sectional description while limiting the number of parameters to a manageable value, each of the five cross-sectional parameters was calculated from the average of the three transections within the anterior, middle, and posterior regions.

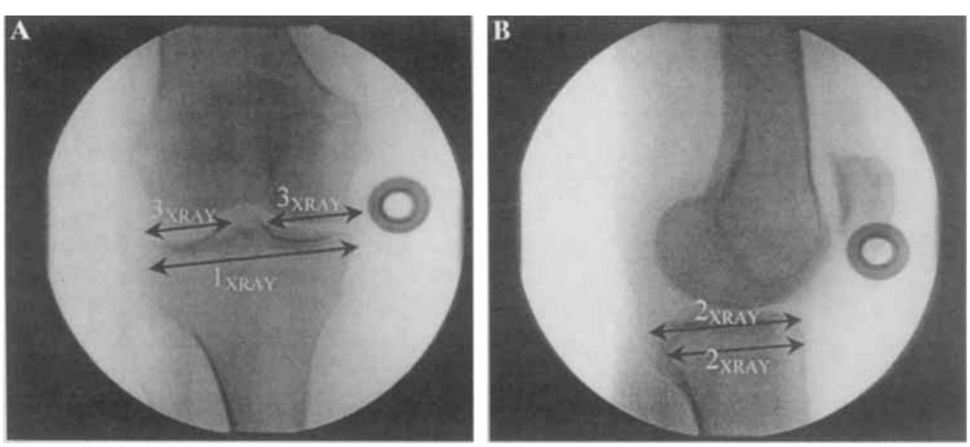

FIG. 2. Roentgenographic images of the test knee with a stainless-steel washer used as a magnification marker. **A:** Anteroposterior roentgenogram used to measure the width of the tibial plateau (1_{xray}), medial tibia (3_{xray}), and lateral tibia (3_{xray}). Medial and lateral widths were measured from the most superior points on the medial and lateral margins of the proximal end of the tibia to the most superior point on the medial and lateral tibial spines, respectively. **B:** Lateral roentgenogram used to measure the depths of the medial (2_{xray}) and lateral (2_{xray}) tibias.

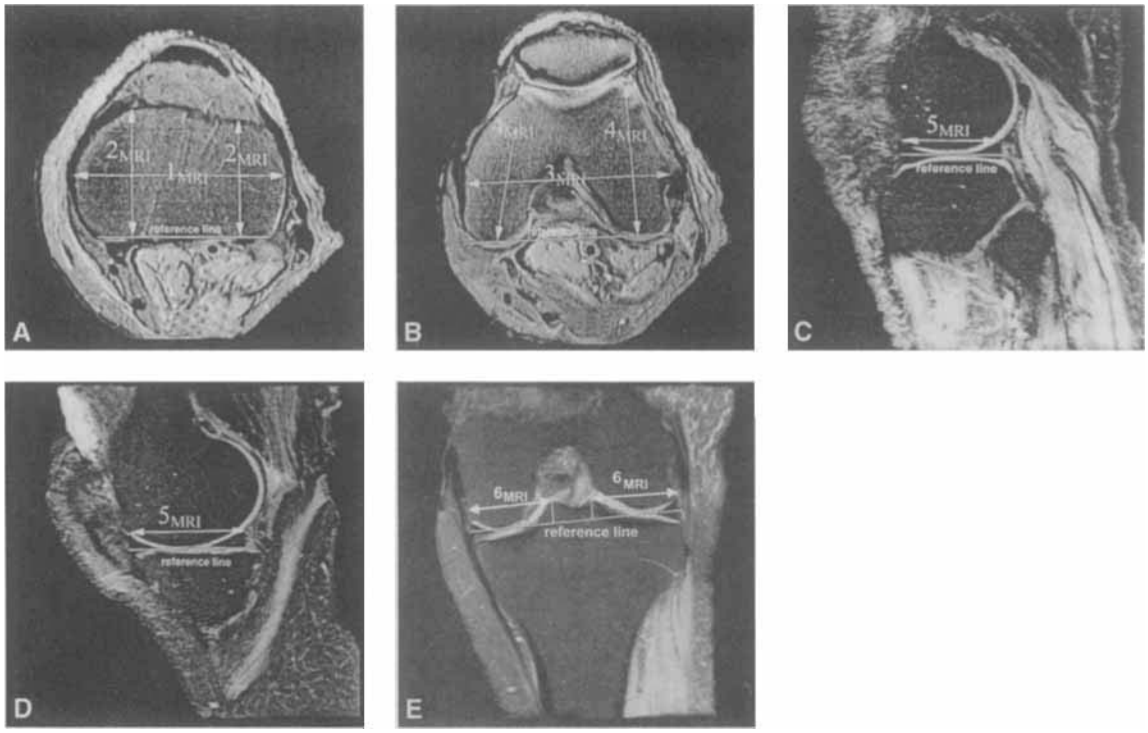

FIG. 3. Magnetic resonance imaging (MRI) showing the transverse, sagittal, and coronal views from which MRI measurements were made. **A:** A reference line was drawn intersecting the most posterior edge of the tibial plateau on the transverse image closest to the joint line, the width of the tibia was measured parallel to the reference line (1_{MRI}), and the depths of the medial (2_{MRI}) and lateral (2_{MRI}) tibial plateaus were perpendicular to the reference line. **B:** A reference line was drawn intersecting the most posterior edge of the femoral condyles on the transverse image with the largest femoral condyles, the width of the femur was measured parallel to the reference line (3_{MRI}), and the depths of the medial (4_{MRI}) and lateral (4_{MRI}) femurs were measured as the distances from the anterior-most point within each section of the femur and the reference line in the center of the posterior condyles. **C:** The depth of the medial meniscus was measured from the sagittal image that best bisected the medial compartment. A reference line was drawn through the tibial plateau, and the depth of the medial meniscus was measured parallel to that line (5_{MRI}). **D:** 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 (5_{MRI}). **E:** The widths of the medial and lateral menisci were 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 two lines were drawn perpendicular to that line and through the lateral and medial menisci. The widths of the medial (6_{MRI}) and lateral (6_{MRI}) menisci were measured from the outer edge of each meniscus to the medial and lateral spines, respectively.

Because the recipient's meniscectomized knee is used to select the meniscal allograft when roentgenography is used, anteroposterior and lateral roentgenograms were obtained from the same knee that was measured with the 3-DCDS. The rotation of the knee was standardized by superimposing the femoral condyles under fluoroscopy. A metal washer was used as a radiopaque marker to correct for magnification.

The two transverse measurements recommended by the tissue bank (Cryolife) were measured and included the width of the tibial plateau (1_{xray}) and the depth of the medial and lateral tibial plateaus (2_{xray}) (Fig. 2). A third measurement, the width of the medial and lateral compartments (3_{xray}), was also acquired because a previous study observed a strong correlation between this bone dimension and meniscal dimensions (16). The roentgenographic measurements were made with a ruler with a precision of 0.5 mm.

Because the recipient's contralateral knee (which has an intact meniscus) is used to select the meniscal allograft when MRI is used, the MRI scans were obtained from the contralateral paired knee that was measured with the 3-DCDS. Imaging was performed with a 1.5-T magnet (Signa; General Electric, Milwaukee, WI, U.S.A.) with a dedicated knee coil. Coronal, sagittal, and transverse scans were obtained by a spin-echo, proton-density weighted technique with a repetition time of 2,300 milliseconds and an echo time of 17 milliseconds. Three-millimeter-thick slices with a 1-mm gap were acquired with use of two signal acquisitions: a 12 by 12-cm field of view and a 256 by 224 matrix.

The six transverse measurements recommended by the tissue bank (Cryolife) included the width of the tibia (1_{MRI}), the depth of the medial (lateral) tibial plateau (2_{MRI}), the width of the femur (3_{MRI}), the depth of the medial (lateral) femur (4_{MRI}), the depth of the medial (lateral) meniscus (5_{MRI}), and the width of the medial (lateral) meniscus (6_{MRI}) (Fig. 3). These measurements were made with the scanner's system software to a resolution of one pixel, approximately 500 μm.

In addition, five cross-sectional measurements were obtained from the anterior, middle, and posterior regions of each meniscus and were used to calculate the five cross-sectional parameters by the previously described technique for the standard parameters. The three slices for measurement were chosen from the sagittal slice that most bisected the anterior region, the coronal slice that most bisected the middle region, and the sagittal slice that most bisected the posterior region.

Data Analysis

To determine whether the standard parameters were independent of one another, a correlation matrix was calculated that included all 19 parameters (four transverse + 15 cross-sectional [five cross-sectional × three regions]). A coefficient of determination (i.e., R-squared value) less than 0.50 was considered to have a weak predictive relationship and was used to support the observation that the two parameters being compared were independent quantities. A coefficient of determination greater than 0.50 was

TABLE 1. *The standard transverse and cross-sectional parameters (mm) used to describe the medial and lateral meniscus*

	Medial meniscus				Lateral meniscus			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Depth	37.99	3.75	30.62	44.08	32.37	5.04	21.97	40.60
Ratio	0.69	0.08	0.57	0.84	0.49	0.09	0.31	0.58
Width-ant	23.60	4.65	17.00	29.00	26.75	3.51	20.00	32.00
Width-post	25.10	2.69	21.50	29.50	28.55	3.66	21.50	35.00
w-ant[a,b]	10.61	2.95	6.75	17.83	12.09	2.24	9.10	16.07
w-mid	11.93	2.70	7.09	15.13	11.77	1.85	8.59	14.14
w-post	14.65	2.69	9.31	19.78	11.42	2.09	8.42	14.19
h-ant[a,b]	6.62	1.49	4.11	8.67	5.93	1.21	3.73	7.54
h-mid	7.08	1.82	4.26	10.33	7.13	1.50	5.31	9.20
h-post	6.01	1.24	4.10	7.50	7.66	2.18	4.22	11.49
b-ant[a,b]	0.15	0.43	–0.43	0.87	0.92	0.41	0.30	1.53
b-mid	–0.24	0.59	–1.82	0.24	0.44	0.49	–0.03	1.61
b-post	0.20	0.71	–1.19	1.54	1.05	0.63	0.28	1.98
h/h_o-ant[b]	1.58	0.62	1.07	2.85	3.04	1.98	1.42	8.17
h/h_o-mid	1.49	0.32	1.07	1.94	1.97	1.19	1.13	4.45
h/h_o-post	2.40	2.46	1.08	9.30	3.40	2.05	1.65	7.71
h_o/w_o-ant[a,b,c]	25.28	6.43	15.77	35.00	16.69	2.83	9.63	19.20
h_o/w_o-mid[b,c]	23.48	3.24	19.47	28.40	21.54	7.59	9.60	33.63
h_o/w_o-post[b,c]	15.49	5.14	4.65	21.60	17.75	7.60	5.20	26.37

Ratio = the ratio of enclosure, width-ant = maximum width of the anterior half of the meniscus, width-post = maximum width of the posterior half of the meniscus, w-ant = maximum width of the anterior region, w-mid = maximum width of the middle region, w-post = maximum width of the posterior region, h-ant = maximum height of the anterior region, h-mid = maximum height of the middle region, h-post = maximum height of the posterior region, b-ant = peripheral bulge of the anterior region, b-mid = peripheral bulge of the middle region, b-post = peripheral bulge of the posterior region, h/h_o-ant = height ratio in the anterior region, h/h_o-mid = height ratio in the middle region, h/h_o-post = height ratio in the posterior region, h_o/w_o-ant = slope in the anterior region, h_o/w_o-mid = slope in the middle region, and h_o/w_o-post = slope in the posterior region.

[a]Significant variation between anterior, middle, and posterior regions of the medial meniscus.

[b]Significant variations between anterior, middle, and posterior regions of the lateral meniscus.

[c]These measurements are in degrees.

considered to indicate a reasonably predictive relationship and the dependence of the two parameters.

To determine how strongly the roentgenographic measurements acquired in the transverse plane predicted the standard transverse parameters of the medial and lateral menisci, a correlation matrix was calculated relating the three roentgenographic measurements specific to each meniscus to the standard transverse meniscal parameters from the same knee. To determine how strongly the MRI measurements acquired in the transverse plane predicted the standard transverse meniscal parameters, a correlation matrix was calculated comparing the six MRI measurements specific for each meniscus with the standard transverse meniscal parameters derived from the opposite paired knee. To determine how strongly the MRI cross-sectional parameters predicted the standard cross-sectional parameters, a correlation matrix was calculated comparing the five MRI measurements per region (i.e., 15 per meniscus) specific for each meniscus with the standard cross-sectional meniscal parameters derived from the opposite paired knee. Again, coefficients of determination (R-squared values) greater than 0.5 were considered to be reasonably predictive.

RESULTS

Standard Parameters

The set of 19 parameters provided independent information about the geometry of the medial and lateral menisci. Of the 171 possible correlations for each meniscus, 92% (157) of the medial and 88% (151) of the lateral meniscus comparisons had R-squared values less than 0.5 and were considered to be independent quantities because of the overall weakness of the correlations.

The transverse parameters were largely unrelated to one another. Of the six correlations for each meniscus, 100% (six of six) and 83% (five of six) were weak for the medial and lateral meniscus, respectively. For the lateral meniscus, the only correlation that was predictive with an R-squared value greater than 0.5 was between the medial-lateral posterior (width-post) and anterior (width-ant) dimensions ($R^2 = 0.86$).

Cross-sectional parameters from one region within a meniscus were only weakly predictive of the same type of cross-sectional parameter in the other two regions. Of the three possible correlations for each of the five cross-sectional parameters between the three regions, 87% (13 of 15) of the parameter combina-

TABLE 2. *Correlation matrix of R-squared values comparing roentgenographic and magnetic resonance imaging measurements with standard transverse parameters for the medial meniscus*

	1_{xray}	2_{xray}	3_{xray}	1_{MRI}	2_{MRI}	3_{MRI}	4_{MRI}	5_{MRI}	6_{MRI}
Depth	**0.70**	**0.82**	**0.76**	**0.71**	**0.64**	**0.52**	**0.68**	**0.82**	**0.64**
Ratio	0.02	0.00	0.00	0.00	0.06	0.22	0.00	0.01	0.01
Width-ant	0.44	0.29	**0.58**	**0.67**	0.21	**0.58**	**0.52**	0.22	0.46
Width-post	0.36	0.18	**0.62**	0.37	**0.50**	0.21	0.12	**0.54**	**0.68**

Boldface numbers represent coefficients of determination greater than or equal to 0.50. 1_{xray} = width of the tibial plateau, 2_{xray} = depth of the medial and lateral tibial plateaus, 3_{xray} = width of the medial and lateral compartments, 1_{MRI} = width of the tibia, 2_{MRI} = depth of the medial tibial plateau, 3_{MRI} = width of the femur, 4_{MRI} = depth of the medial femur, 5_{MRI} = depth of the medial meniscus, 6_{MRI} = width of the medial meniscus, ratio = the ratio of enclosure, width-ant = maximum width of the anterior half of the meniscus, and width-post = maximum width of the posterior half of the meniscus.

tions for the medial meniscus and 80% (12 of 15) of those for the lateral meniscus were weakly correlated. Only the correlation between the height in the anterior region (h-ant) and the height in the middle region (h-mid) had an R-squared value greater than 0.5 (R^2 = 0.54) across the regions for both the lateral and medial menisci. The independence of the same parameter across regions indicated that the shape of the cross section was region-dependent.

For the most part, the five parameters within a region also were only weakly predictive of each other. Of the 30 possible correlations between the five cross-sectional parameters of the medial meniscus within a region (10 correlations/region × three regions), 90% (27 of 30) were weakly related. Of the 30 possible correlations between the five cross-sectional parameters of the lateral meniscus within a region, 87% (26 of 30) were weakly related. The only correlation that was predictive with an R-squared value greater than 0.5 for both the lateral and medial menisci was between the slope (h_o/w_o-post) and height ratio (h/h_o-post) in the posterior region (lateral: R^2 = 0.78; medial: R^2 = 0.66).

The four transverse parameters were weakly related to the cross-sectional parameters of the medial and lateral menisci. The transverse parameters were weakly predictive of 80% (12 of 15) of the medial cross-sectional parameters. The three medial cross-sectional parameters that were predicted with R-squared values greater than 0.5 by the transverse parameters included the maximum width of the middle region (w-mid, R^2 = 0.51), the maximum height of the posterior region (h-post, R^2 = 0.52), and the slope of the posterior region (h_ow_o-post, R^2 = 0.54). Similarly, the transverse parameters were weakly predictive of 73% (11 of 15) of the cross-sectional parameters of the lateral meniscus. The four lateral cross-sectional parameters that were predicted with R-squared values greater than 0.5 by the transverse parameters included the maximum height of the anterior region (h-ant, R^2 = 0.62), the peripheral bulge of the middle region (b-mid, R^2 = 0.50), the slope of the anterior region (h_o/w_o-ant, R^2 = 0.63), and the maximum width of the middle region (w-mid, R^2 = 0.71).

Both the transverse and cross-sectional meniscal parameters were highly variable between specimens (Table 1). In general, the cross-sectional parameters exhibited greater variability than the transverse parameters. The transverse parameters had a ratio of maximum to minimum that was less than 2.0 for both the medial (range: 1.4-1.7) and lateral (range: 1.6-1.9) menisci. In contrast, the cross-sectional parameters had greater variability; the ratio of maximum to minimum was greater than 2 in 73% (11 of 15) of the parameters for the medial (range: 0.1-8.6)

TABLE 3. *Correlation matrix of R-squared values comparing roentgenographic and magnetic resonance imaging measurements with standard transverse parameters for the lateral meniscus*

	1_{xray}	2_{xray}	3_{xray}	1_{MRI}	2_{MRI}	3_{MRI}	4_{MRI}	5_{MRI}	6_{MRI}
Depth	0.32	0.25	**0.50**	0.26	0.49	0.19	0.46	**0.50**	**0.54**
Ratio	0.02	0.08	0.08	0.03	0.02	**0.62**	0.37	0.11	0.10
Width-ant	0.40	0.11	0.48	**0.52**	0.24	0.36	0.41	0.12	**0.66**
Width-post	0.36	0.21	**0.56**	0.47	0.20	0.44	**0.61**	0.06	**0.76**

Boldface numbers represent coefficients of determination greater than or equal to 0.50. 1_{xray} = width of the tibial plateau, 2_{xray} = depth of the medial and lateral tibial plateaus, 3_{xray} = width of the medial and lateral compartments, 1_{MRI} = width of the tibia, 2_{MRI} = depth of the lateral tibial plateau, 3_{MRI} = width of the femur, 4_{MRI} = depth of the lateral femur, 5_{MRI} = depth of the lateral meniscus, 6_{MRI} = width of the lateral meniscus, ratio = the ratio of enclosure, width-ant = maximum width of the anterior half of the meniscus, and width-post = maximum width of the posterior half of the meniscus.

TABLE 4. *Correlation matrix of R-squared values comparing cross-sectional parameters determined from MRI measurements with standard cross-sectional parameters for the medial meniscus*

	MRI measurements														
	w-ant	w-mid	w-post	h-ant	h-mid	h-post	b-ant	b-mid	b-post	h/h_o-ant	h/h_o-mid	h/h_o-post	h_o/w_o-ant	h_o/w_o-mid	h_o/w_o-post
w-ant	**0.67**	0.35	0.12	0.00	0.02	0.02	0.04	0.39	0.16	0.28	0.11	0.00	0.14	0.05	0.01
w-mid	0.25	**0.67**	0.04	0.02	0.16	0.00	0.00	0.28	0.22	0.01	0.00	0.02	0.14	0.01	0.00
w-post	0.44	**0.50**	0.19	0.27	0.07	0.02	0.22	0.22	0.04	0.00	0.10	0.01	0.03	0.28	0.02
h-ant	0.15	0.34	0.02	0.15	0.26	0.00	0.00	0.01	0.00	0.01	0.11	0.00	0.00	0.31	0.00
h-mid	0.03	0.05	0.06	0.13	**0.59**	0.29	0.06	0.02	0.02	0.29	0.38	0.13	0.14	0.06	0.05
h-post	0.09	0.05	0.12	0.13	0.01	**0.67**	0.05	0.08	0.04	0.01	0.01	**0.60**	0.02	0.29	0.24
b-ant	0.07	0.43	0.17	0.04	0.30	0.04	0.45	0.07	0.00	0.13	0.00	0.00	0.28	0.18	0.28
b-mid	0.17	0.19	0.10	0.04	0.30	0.06	0.22	0.12	0.13	0.29	0.04	0.18	0.31	0.08	0.00
b-post	0.06	0.44	0.02	0.03	0.31	0.01	0.11	**0.69**	**0.62**	0.01	0.00	0.06	0.11	0.02	0.04
h/h_o-ant	0.14	0.05	0.04	0.03	0.01	0.08	0.04	0.06	0.18	0.10	0.01	0.09	0.06	0.36	0.13
h/h_o-mid	0.32	0.12	0.04	0.06	0.01	0.02	0.14	0.24	0.43	0.32	0.12	0.05	0.19	0.02	0.14
h/h_o-post	0.03	0.01	0.00	0.02	0.17	0.07	0.01	0.22	0.48	0.02	0.01	0.04	0.03	0.10	0.08
h_o/w_o-ant	0.08	0.05	0.03	0.11	0.07	0.08	0.03	0.00	0.04	0.01	0.05	0.04	0.12	0.36	0.03
h_o/w_o-mid	0.02	0.10	0.05	0.01	0.31	**0.68**	0.02	0.17	0.03	0.10	0.26	**0.53**	0.00	0.15	0.05
h_o/w_o-post	0.24	0.00	0.27	0.15	0.02	0.20	0.13	0.03	0.15	0.05	0.04	0.31	0.02	0.00	0.15

Boldface numbers represent coefficients of determination greater than or equal to 0.50. MRI = magnetic resonance imaging, w-ant = maximum width of the anterior region, w-mid = maximum width of the middle region, w-post = maximum width of the posterior region, h-ant = maximum height of the anterior region, h-mid = maximum height of the middle region, h-post = maximum height of the posterior region, b-ant = peripheral bulge of the anterior region, b-mid = peripheral bulge of the middle region, b-post = peripheral bulge of the posterior region, h/h_o-ant = height ratio in the anterior region, h/h_o-mid = height ratio in the middle region, h/h_o-post = height ratio in the posterior region, h_o/w_o-ant = slope in the anterior region, h_o/w_o-mid = slope in the middle region, and h_o/w_o-post = slope in the posterior region.

and lateral (range: 1.6-53.7) menisci.

Standard Parameters and Image Dimensions

The two roentgenographic measurements used by the tissue bank for each meniscus (1_{xray} and 2_{xray}) were poor predictors of the four standard transverse parameters used to describe the geometry of the medial and lateral menisci. For the medial meniscus, only 25% (one of four) of the standard transverse parameters were predicted by the roentgenographic measurements obtained in the transverse plane (Table 2). For the lateral meniscus, none of the standard transverse parameters were predicted by the roentgenographic measurements (Table 3).

Including the third transverse roentgenographic measurement for each meniscus (i.e., width of the medial or lateral compartments [3_{xray}]) (16) with the two transverse measurements recommended by the tissue bank improved the ability of transverse roentgenographic measurements to predict the standard transverse parameters of the menisci. For the medial meniscus, 75% (three of four) instead of 25% of the standard transverse parameters were predicted by three transverse roentgenographic measurements for the medial meniscus (Table 2). For the lateral meniscus, 50% (two of four) instead of none of the standard transverse parameters were predicted by three transverse roentgenographic measurements (Table 3).

The transverse MRI measurements were much better predictors of the four standard transverse parameters than were the transverse roentgenographic measurements. For the medial meniscus, only two of six transverse MRI measurements from the contralateral knee were required to predict 75% (three of four) of the standard transverse parameters (Table 2). For the lateral meniscus, only two of six transverse MRI measurements from the contralateral knee were required to predict 100% (four of four) of the standard transverse parameters (Table 3).

For the medial meniscus, the MRI cross-sectional parameters predicted all three standard parameters for width (w-ant, w-mid, and w-post), the standard parameters for height for the middle and posterior regions (h-mid and h-post), the standard parameter for slope for the middle region (h_ow_o-mid), and the standard parameter for bulge for the posterior region (b-post) (Table 4). For the lateral meniscus, the MRI cross-sectional parameters predicted all three standard parameters for width, all three standard parameters for height, and the standard parameter for slope for the middle region (Table 5). In general, the standard cross-sectional meniscal parameters were predicted by the same parameter measured from MRI.

DISCUSSION

Because meniscal geometry is one important determinant of tibiofemoral contact mechanics, the broad goals of this study were to evaluate and improve pro-

TABLE 5. *Correlation matrix of R-squared values comparing cross-sectional parameters determined from MRI measurements with standard cross-sectional parameters for the lateral meniscus*

	MRI measurements														
	w-ant	w-mid	w-post	h-ant	h-mid	h-post	b-ant	b-mid	b-post	h/h_o-ant	h/h_o-mid	h/h_o-post	h_o/w_o-ant	h_o/w_o-mid	h_o/w_o-post
w-ant	**0.57**	**0.50**	0.01	0.09	0.23	0.04	0.00	0.00	0.01	0.05	0.06	0.05	0.03	0.04	0.05
w-mid	**0.53**	0.39	0.04	0.09	0.25	0.06	0.05	0.25	0.02	0.00	0.09	0.03	0.20	0.01	0.00
w-post	0.05	**0.65**	**0.68**	0.37	0.17	0.41	0.00	0.00	0.01	0.00	0.20	0.01	0.01	0.02	0.01
h-ant	**0.62**	0.40	0.08	**0.62**	0.37	0.17	0.18	0.00	0.08	0.00	0.00	0.13	0.13	0.20	0.16
h-mid	0.29	0.32	0.13	0.19	**0.58**	0.12	0.00	0.01	0.00	0.04	0.07	0.23	0.15	0.27	0.29
h-post	0.01	0.39	**0.56**	0.41	0.10	**0.77**	0.01	0.27	0.00	0.01	0.09	0.01	0.00	0.06	0.07
b-ant	0.13	0.28	0.06	0.01	0.05	0.00	0.13	0.05	0.25	0.01	0.09	0.04	0.03	0.08	0.05
b-mid	0.26	0.15	0.09	0.37	0.11	0.18	0.31	0.22	0.01	0.01	0.01	0.04	0.40	0.00	0.01
b-post	0.32	0.00	0.18	0.01	0.01	0.00	0.08	0.01	0.42	0.22	0.07	0.15	0.00	0.03	0.17
h/h_o-ant	0.07	0.00	0.05	0.06	0.10	0.02	0.22	0.07	0.08	0.01	0.05	0.18	0.18	0.21	0.13
h/h_o-mid	0.29	0.29	0.05	0.43	0.10	0.16	0.10	0.03	0.00	0.00	0.00	0.03	0.11	0.00	0.00
h/h_o-post	0.33	0.43	0.13	0.48	0.13	0.24	0.06	0.05	0.00	0.00	0.00	0.03	0.07	0.01	0.00
h_o/w_o-ant	0.15	0.19	0.09	0.42	0.33	0.04	0.06	0.08	0.04	0.24	0.00	0.00	0.21	0.09	0.00
h_o/w_o-mid	0.06	0.20	0.06	0.22	0.13	0.15	0.05	0.05	0.00	0.00	0.02	0.00	0.01	**0.60**	0.17
h_o/w_o-post	0.30	0.12	0.06	0.49	0.12	0.29	0.31	0.08	0.23	0.01	0.00	0.34	0.12	0.07	0.38

Boldface numbers represent coefficients of determination greater than or equal to 0.50. MRI = magnetic resonance imaging, w-ant = maximum width of the anterior region, w-mid = maximum width of the middle region, w-post = maximum width of the posterior region, h-ant = maximum height of the anterior region, h-mid = maximum height of the middle region, h-post = maximum height of the posterior region, b-ant = peripheral bulge of the anterior region, b-mid = peripheral bulge of the middle region, b-post = peripheral bulge of the posterior region, h/h_o-ant = height ratio in the anterior region, h/h_o-mid = height ratio in the middle region, h/h_o-post = height ratio in the posterior region, h_o/w_o-ant = slope in the anterior region, h_o/w_o-mid = slope in the middle region, and h_o/w_o-post = slope in the posterior region.

cedures for selecting meniscal allografts by examining how well these procedures provide an allograft that matches the size and shape of the original meniscus. To accomplish these goals, an experimental approach was used whereby standard parameters were measured for the medial and lateral menisci. Then, measurements from roentgenograms and MRI scans were tested for their ability to predict the standard parameters. The four most important findings from this study were that (a) the 19 standard parameters were largely independent, (b) two transverse roentgenographic measurements cannot predict the standard transverse parameters of a meniscus, (c) three transverse roentgenographic measurements improved the prediction of standard transverse meniscal parameters but not equal to MRI, and (d) the transverse and cross-sectional MRI parameters predicted the standard transverse and cross-sectional parameters, respectively, of the medial and lateral menisci. Before discussing the importance of these findings, several methodological issues should be reviewed.

Methodological Issues

The evaluation of any procedure for predicting meniscal geometry requires a standard that accurately describes the size and shape of the menisci. With an error of 15 μm, the 3-DCDS measured the three-dimensional coordinates of the surface of the menisci and tibial plateau with sufficient accuracy to calculate standard meniscal parameters (8). From these coordinates, each meniscus was reconstructed and then 19 standard parameters (four transverse and 15 cross-sectional) were used to describe the three-dimensional geometry of the medial and lateral menisci.

The 19 standard parameters used in this study should not be considered the optimum set for describing meniscal geometry. For example, the decision to analyze cross-sectional parameters across three regions fulfilled a study objective by detecting significant differences in cross-sectional shape within a meniscus. However, significant differences might also have been detected with use of smaller regions, which, although not a requirement for the current study, may be important if future studies define a need for more refined characterization of meniscal cross-sectional shape.

In evaluating the efficacy of the roentgenographic and MRI measurements to predict the geometric parameters, a coefficient of determination of 0.5 was chosen to be a reasonable predictor for this study. After inspection of the regression plots for various coefficients of determination and observation that coefficients greater than or equal to 0.5 were significant to $p < 0.05$, coefficients greater than 0.5 were considered to be reasonably predictive. However, the degree of correlation adequate to restore normal contact pressure with an allograft is unknown.

Although the measurements from the roentgenograms and MRI scans were obtained from the intact joint and measurements with the 3-DCDS were obtained without the femur because the joint was disarticulated, it is unlikely that this difference in the condition of the joint (i.e., presence or absence of the femur) affected the conclusions of the study. Both the MR images and roentgenograms were taken while the intact knee was unloaded, and therefore no contact pressure existed across the joint. Without pressure, deformation of the meniscal tissue by the femur should have been negligible since the meniscus is relatively inelastic (tensile modulus = 150 MPa [23]). This expectation was confirmed by the fact that the standard transverse parameters obtained with the 3-DCDS were predicted by the MRI transverse measurements, showing that the transverse dimensions of the meniscus in the intact joint were similar to those in the disarticulated joint. Moreover, the cross-sectional height and width of the menisci in the intact knee as determined by MRI were similar to those in the disarticulated knee. These two observations indicate that the geometry of the meniscus was not strongly influenced by the presence or absence of the femur.

Interpretation of Results

Even though the addition of one transverse measurement improved the ability of roentgenography to predict the standard transverse parameters, roentgenography still remained inferior to MRI for predicting transverse parameters for two reasons. One reason was that more standard transverse parameters for the lateral meniscus were predicted by MRI (50 compared with 100%). A second reason was that MRI predicted all parameters with R-squared values either equal to or greater than those for roentgenography (Tables 2 and 3).

MRI was also better than roentgenography for predicting cross-sectional meniscal shape. Because standard transverse parameters predicted only a few of the standard cross-sectional parameters (i.e., 20% of medial and 27% of lateral) and because roentgenographic measurements were only moderately predictive of standard transverse parameters (Tables 2 and 3), it was expected that the transverse measurements from roentgenograms would be ineffective at predicting cross-sectional meniscal shape. Indeed, in other correlation analyses not tabulated herein, only two of 15 (13%) standard medial cross-sectional parameters and three of 15 (20%) standard lateral meniscal parameters were predicted by transverse roentgenographic measurements. In contrast, the cross-sectional measurements from MRI were predictive of seven of 15 (47%) standard medial and seven of 15 (47%) standard lateral cross-sectional parameters of the contralateral meniscus (Tables 4 and 5). Including the correlations between the MRI transverse measurements and the standard cross-sectional parameters increased the number of standard cross-sectional parameters predicted to eight of 15 (53%) for both the medial and lateral menisci.

The finding that MRI is a better imaging modality than roentgenography for predicting cross-sectional parameters has possible clinical implications. In two previous studies, the contact mechanics were not restored to normal with a meniscal allograft because the cross-sectional shape was not matched to the original meniscus (1,9). Therefore, if restoring normal tibiofemoral contact at the time of implantation is important to long-term clinical outcome, then tissue banks will need to use MRI rather than roentgenography whenever possible to more closely match the transverse parameters and the cross-sectional shape of the allograft to the original meniscus.

The inability of the MRI cross-sectional parameters of bulge, height ratio, and slope to predict the same standard cross-sectional parameters was most likely due to the higher measurement error of the MRI (500 μm) compared with that of the 3-DCDS (15 μm). A precise measurement of the bulge could not be made with MRI because the average bulge was just 1 mm and the measurement error was 0.5 mm. Although the MRI software was able to precisely measure the larger dimensions of width (range: 10.6-14.7 mm) and height (range: 5.9-7.7 mm) of the menisci because of the larger dimensions (Table 1), the ratios of height and slope from MRI were poor predictors of the same standard cross-sectional parameters. This poor predictability may have been due to error compounded from calculating each ratio from two measurements that were in greater error with MRI than with the 3-DCDS.

The results of this study demonstrate conclusively that MRI is a better imaging technology than roentgenography for selecting medial and lateral meniscal allografts when the goal is to provide an implant that best matches the geometry of the original meniscus. For both compartments of the knee, the tissue bank can best select an allograft that matches the uninjured meniscus by measuring two transverse (i.e., width of the meniscus and femur) and six cross-sectional (i.e., width and height for the anterior, middle, and posterior regions) dimensions from an MRI of the uninjured contralateral knee.

This study focused on the procedures for selecting an allograft so that the graft better matches the geometry of the original meniscus; however, this focus does not imply that geometry is the only important biomechanical consideration in the selection of an allograft. In addition to geometry, material properties of the tissue may also play an important role in the restoration of contact mechanics with a meniscal replacement.

Collagen fibers are arranged predominantly in the circumferential direction. These fibers function to support the large hoop stresses that are important to the distribution of contact stresses within the knee joint. Mathematical models that have studied the role of the meniscus in the load transmission of the tibiofemoral joint confirm that the most important material property is the circumferential tensile modulus (19,23). Accordingly, because of the importance of the circumferential tensile modulus in determining the load-bearing role of the meniscus and because of the wide variation in this property between specimens (6), the material properties also may be an important consideration in the selection of meniscal replacements.

Although biomechanical considerations such as the geometry and material properties may be important in the selection of meniscal allografts, other biological factors after implantation may influence clinical outcome. Biological factors include the ability (a) to be accepted with minimum immunological response, (b) following preservation, to repopulate with host cells that restore normal synthetic activity, and (c) to heal to surrounding tissue (9,20,22). In animal studies (2,9) and clinical follow-up studies on human patients (5,7,17,20), meniscal allografts have shown the potential to meet these biological criteria. However, incomplete peripheral healing and shrinkage have been observed (11,12,20).

Inasmuch as surgical implantation of meniscal allografts is demanding technically (26) and is generally performed on patients who have had previous knee surgery, the skill of the surgeon in performing the implantation and the condition of the joint should be recognized as final important factors for clinical success. For example, either poor suturing of the peripheral rim or attachment to avascular tissue could account for some of the undesirable consequences of meniscal transplantation observed clinically, such as incomplete peripheral healing (7). Considering that it is unknown how all of the biomechanical, biological, surgical, and patient factors will ultimately interact to dictate surgical outcome, tissue banks should use the new procedures described in the present study for the selection of meniscal allografts predicated on the assumption that a successful clinical outcome depends on how well an allograft matches the size and shape of the original meniscus.

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