Topographic Matching of Osteochondral Allograft Transplantation Using Lateral Femoral Condyle for the Treatment of Medial Femoral Condyle Lesions: A Computer-Simulated Model Study

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Purpose: The purpose of this study was to determine whether lateral femoral condyle (LFC) osteochondral allografts (OCAs) would have a similar articular cartilage contour and resulting subchondral bone contour when compared with medial femoral condyle (MFC) allografts for the treatment of MFC chondral defects. **Methods:** In this controlled laboratory study, human femoral hemi-condyles (10 MFCs and 8 LFCs) were divided into 4 groups: MFC recipient, MFC donor, ipsilateral LFC donor, and contralateral LFC donor. Computed tomography (CT) images were obtained for each, and 3D CT models were created and exported into point-cloud models. Three circular defect and graft models were created on each condyle at 3 locations (0°, 45° posterior, and 90° posterior regions). The graft model in each donor group was virtually placed on the MFC recipient defect model. The least distances of the articular cartilage surface between the graft and the defect models and the resulting mean least distance of the subchondral bone surface were calculated. **Results:** The mean least distance of the articular cartilage surface was less than 0.5 mm in all donor—recipients, and there was no significant difference among donor groups. Although the mean least distance of the subchondral bone surface was significantly greater than the articular cartilage surface in all donor groups ($P < .001$), there was no significant difference among donor groups. **Conclusion:** Ipsilateral and contralateral LFC grafts provided similar articular cartilage surface and resulting subchondral bone surface matching with that of MFC grafts, suggesting that LFCs could be a potential source of OCA for the treatment of MFC lesions. **Clinical Relevance:** Ipsilateral and contralateral LFCs can be suitable donor sites for the treatment of MFC lesions with OCAs.

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Treatment of focal chondral or osteochondral defects is challenging because articular cartilage has a limited capacity to repair itself after injury. Osteochondral allograft (OCA) transplantation has been performed to restore the articular cartilage surface for large chondral or osteochondral lesions.[1-8] In the situation of OCA transplantation for femoral condyle lesions, the graft is typically ordered based on the same side (right or left), condyle (medial or lateral), and size (the affected condylar width).[3,6]

The cartilage lesion in the knee joint can be found most frequently in medial femoral condyle (MFC).[9-12] This suggests that OCAs are commonly needed for MFC lesions, although the LFC are more available for grafts. A limited availability of OCAs for MFC lesions result in increased patient wait time and subsequently deterioration of lesions. To resolve this problem, LFCs may be a suitable graft source for the treatment of MFC lesions.

An ideal match for OCA transplantation would be a perfect congruous relationship between the graft and

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Table 1. Demographic Data of the Recipient and Donor Condyles

	Recipient Condyle	Donor Condyle		
	MFC	MFC	Ipsilateral LFC	Contralateral LFC
n	7	7	7	7
Side, right: left	4:3	4:3	4:3	3:4
Condylar width, mm	24.39 ± 1.09 (23.50–26.50)	24.81 ± 1.16 (23.60–27.01)	28.45 ± 1.40 (26.80–30.10)	28.35 ± 1.28 (26.80–30.00)
P value*		0.495	<.001†	<.001†
Effect size‡			3.23	3.32

NOTE. Data presented as mean ± standard deviation (range).
MFC, medial femoral condyle; LFC, lateral femoral condyle.
*Unpaired Student *t*-testing was performed to compare the condylar width between the recipient and donor condyles.
†Statistically significant difference from the recipient condyle ($P < .05$).
‡Effect size was calculated when a Student t-test exceeded the minimal importance difference value.

the recipient. However, LFC grafts for MFC lesions may provide greater mismatch than MFC grafts because the structures of MFCs and LFCs have shown that the shape, curvature, and size were different.[13-17] A few studies investigated the surface matching to use the LFCs as OCAs to treat MFC lesions.[18,19] Mologne et al.[19] reported that a contralateral LFC graft matched as well as an MFC graft for 20-mm defects in the weightbearing portion of the MFC. However, the topographic matching of different LFC graft size at different locations has yet to be investigated.

The purpose of this study is to determine whether lateral femoral condyle (LFC) osteochondral allografts would have a similar articular cartilage contour and resulting subchondral bone contour when compared with medial femoral condyle (MFC) allografts for the treatment of MFC chondral defects. Our hypotheses were that (1) the condylar width in the LFC was larger than that in the MFC, (2) there was no difference in the articular cartilage surface mismatch between MFC and LFC grafts, and (3) the subchondral bone surface mismatch was greater than the articular cartilage mismatch; however, there was no significant difference in the articular cartilage surface mismatch between MFC and LFC grafts.

Material and Methods

Specimen Preparation

Eighteen femoral hemi-condyles with intact articular cartilage surface (10 MFCs and 8 LFCs) were prepared from a donor tissue bank (AlloSource, Denver, CO) according to the company's standard protocol for planned implantation. Condylar width was measured with a digital micrometer 10 mm distal to the most superior aspect of the notch, which is the same method used by donor tissue suppliers. Four groups were created: MFC recipient, MFC donor, ipsilateral LFC donor, and contralateral LFC donor (Table 1). Combinations in MFC donor–MFC recipient were created to match to the ipsilateral side (right MFC donor matched to right MFC recipient; left MFC donor matched to left MFC recipient) and size (the donor condylar width was larger up to 1.0 mm than the recipient condylar width). Ten combinations were created in MFC donor–MFC recipient. Of them, 3 combinations were excluded because the difference between the donor and recipient condylar width was more than 1.0 mm. The remaining 7 combinations were used for the following analysis. Ipsilateral LFC donors and contralateral LFC donors were matched with MFC recipients (right ipsilateral LFC donor matched to right MFC recipient; left ipsilateral LFC donor matched to left MFC recipient; left contralateral LFC recipient donor matched to right MFC recipient; right contralateral LFC donors matched to left MFC recipient) so that the differences in condylar width were minimized (n = 7 in each group).

Computer Model Creation of the Distal Femoral Articular Surfaces

Computed tomography (CT) (BrightSpeed; GE Healthcare, Wauwatosa, WI) images of the specimens were acquired in the coronal, axial, and sagittal planes by use of 0.625-mm continuous slices (120 kV, 100 mA, 1.0-second duration, 20-cm field of view, 512 × 512 matrices). Three-dimensional (3D) CT models of the femoral hemi-condyle were then created and exported into point-cloud models using a 3D reconstruction software program (Mimics, Materialise Inc., Leuven, Belgium) (Fig 1). A local coordinate system was set on the distal femoral hemi-condyle. Eigenvectors of the distal femoral hemi-condyle point-cloud data set were calculated to determine the orientation of orthogonal principal axes (x-, y-, and z-axes) of the distal femoral hemi-condyle. A plane including the most distal point was defined as a para-coronal plane (blue plane in Fig 2). A plane including the most posterior point was defined as a para-transverse plane (red plane in Fig 2). The parasagittal plane (green plane in Fig 2) was defined as a plane including the centroid of the articular surface model. An intersection of these planes was defined as an origin of the local coordinate system. This system was further transferred to a spherical coordinate system, with the most distal point as the "South pole." The definition of the coordinate system and the

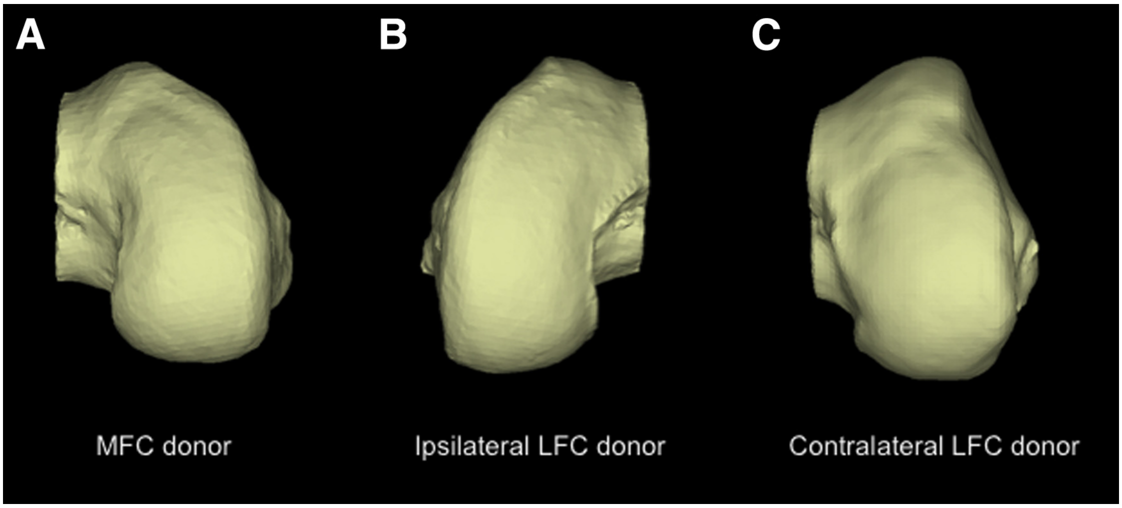

Fig 1. A 3-dimensional computed tomography model of the donor condyle for the right medial femoral condyle (MFC) lesion; the MFC donor (A), the ipsilateral lateral femoral condyle (LFC) donor (B), and the contralateral LFC donor (C). The en face of projection of the femoral hemi-condyle surface was used for point-cloud data analysis.

subsequent 3D model creation and geometry matching were performed using a custom-written program coded by in Microsoft Visual C ++ 2005 with Microsoft Foundation Class programming environment (Microsoft Corp., Redmond, WA).

3D CT Computer Model Creation of the Graft and the Defect

Circular articular cartilage and subchondral bone graft models were created in each point cloud model of the donor condyle with 3 different diameters (15 mm, 20 mm, and 25 mm) at 3 locations: center of the medial condyle at 0°, 45° posterior, and 90° posterior (Fig 3). The femoral hemi-condyle was virtually rotated 0°, 45°, and 90° posteriorly around the origin of the local coordinate system about the x-axis. The centroid of the articular cartilage graft model was then determined as the most distal point at each rotation angle. The point-cloud data within a distance of 7.5 mm, 10.0 mm, and 12.5 mm from the centroid were defined as the dataset of the graft model. The centroids were adjusted along with the x-axis so that graft models were entirely located on the condyle. Subchondral bone graft models were created on the same location as articular cartilage graft models. Similarly, circular articular cartilage and subchondral bone defect models were created in the MFC recipient with the same size at the same locations.

3D Articular Cartilage and Subchondral Bone Surface Matching of Graft–Defect Models

Three-dimensional surface topographies of the articular cartilage surface and resulting subchondral bone surfaces were compared between graft and defect models using the previous procedures (Fig 4).[20] In each MFC defect models, 9 combinations were simulated (15-, 20-, and 25-mm defects × 3 locations), resulting in 189 graft-defect comparative combinations being tested (9 combinations × 7 MFC donor + 9 combinations × 7 ipsilateral LFC donor + 9 combinations × 7 contralateral LFC donor). The MFC and LFC graft models were virtually placed on the surface of the MFC defect model (Fig 5A). Orientation of the graft model was adjusted so that its axis matched that of the defect site. Least distances between the graft and the defect models were calculated (Fig 5B). The least distances were defined as the shortest distance from the point in question to the corresponding point in space, where a perfect congruent match would equal a least distance of 0.00 mm for given data points on the simulated articular cartilage surface.

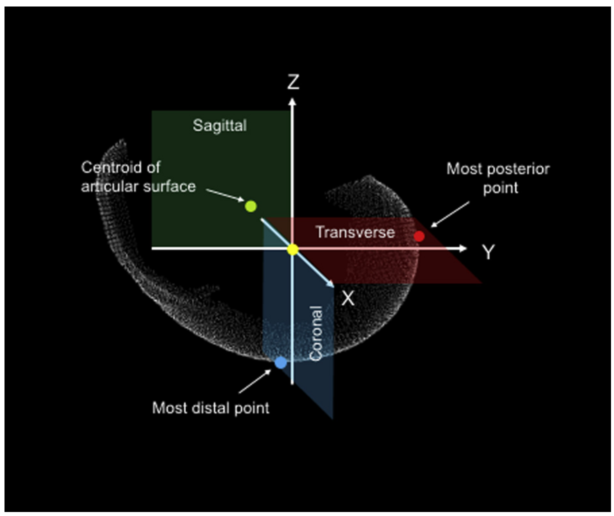

Fig 2. A point-cloud model of the distal femoral hemi-condyle (white points). An orthogonal local coordinate system (x-, y- z-axes) of the femoral hemi-condyle was set with the orientation determined by the intersection (yellow dot) of three planes (blue, red, and green planes). The most distal (along the z-axis) point was determined as the 0° point (cyan blue dot).

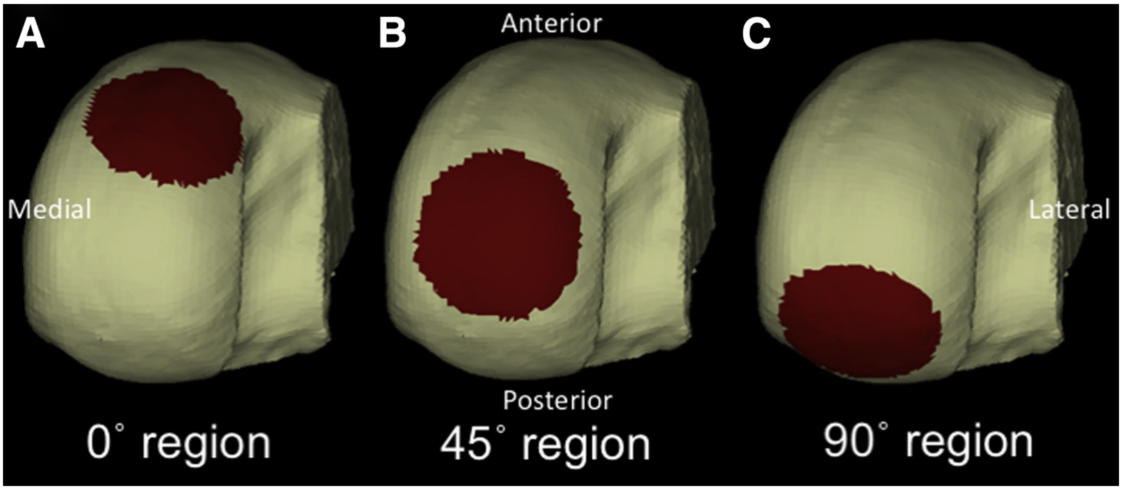

Fig 3. Circular defect models in the medial femoral condyle (MFC) and graft models in the MFC and the lateral femoral condyle (LFC) were created at 3 locations. The femoral hemi-condyle was virtually rotated 0° (A), 45° (B), and 90° (C) posteriorly around the centroid of the local coordinate system (yellow dot). The centroid of the circular defect and graft were determined as the most distal point (cyan blue dot). Three different diameter (15 mm, 20 mm, and 25 mm) circular cartilage and subchondral bone models (red region) were created on each condyle.

A mean value of the least distances was calculated for each position of the graft model. The mean least distance of subchondral bone surface in each point was calculated simultaneously. The graft model was then rotated 360° around the axis perpendicular to the articular cartilage surface in 1° increments, and the least distance of articular cartilage surface and the resulting least distance of subchondral bone surface were calculated at each rotating angle (Fig 5C). This was performed for all combinations of simulated defect models and graft models.

Statistical Analysis

Statistical analysis was performed using Excel 2010 (Microsoft Corp, Redmond, WA) and JMP software (v12.0; SAS Institute, Cary, NC). Unpaired Student *t*-tests were performed to compare condylar width between the recipient condyle and each donor condyle (MFC donor, ipsilateral LFC donor, and contralateral LFC donor). Within each group, paired Student *t*-tests were performed to compare the difference in the mean least distance between the articular cartilage surface and the subchondral bone surface in each size (15, 20, and 25 mm) at each location (0°, 45°, and 90°). One-way analysis of variance was performed to compare the mean least distance among sizes within each group and to compare the mean least distance among donor groups. If the analysis of variance result was significant, post hoc analysis was performed with a Tukey test. The data were presented as mean ± standard deviation, and the level of significance for all analyses was set at $P < .05$.

Results

Differences of the Condylar Width Between the Recipient and Donor

The mean condylar width in the recipient and the donor condyles is shown in Table 1. Although the difference of condylar width between the recipient and donor was 0.42 ± 0.27 mm in the MFC donor, the

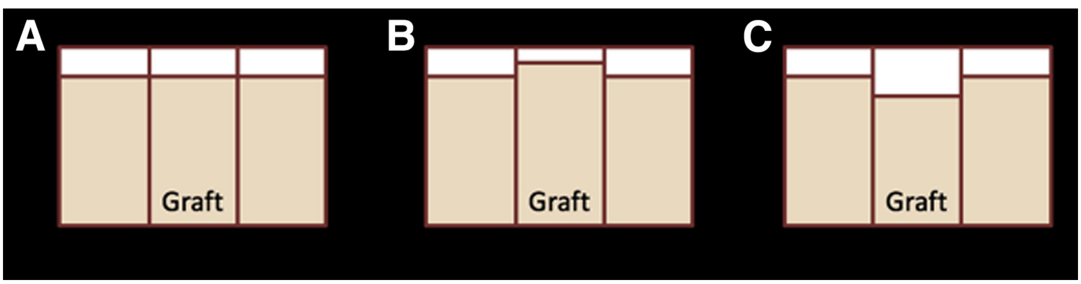

Fig 4. Articular cartilage surface and resulting subchondral bone surface matching. (A) Articular cartilage surface and subchondral bone surface matches between the graft and the recipient. (B) Articular cartilage surface matches, however subchondral bone surface of the graft elevates from that of the recipient. (C) Articular cartilage surface matches; however, subchondral bone surface of the graft sinks from that of the recipient.

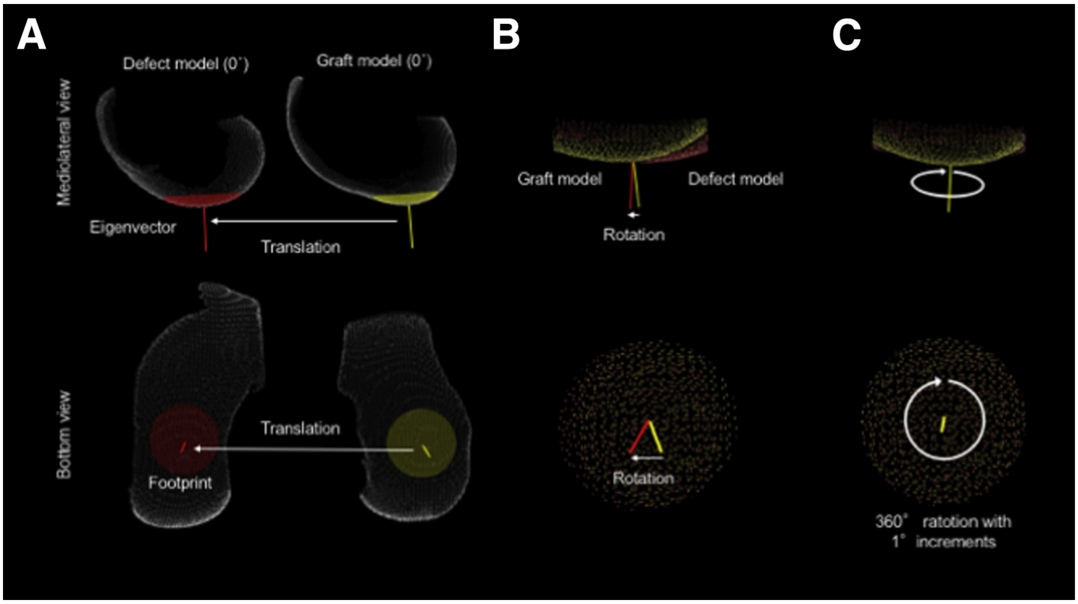

Fig 5. Three-dimensional surface geometries of the articular surface and subchondral bone surface were compared between the defect and the graft models. (A) The defect model was virtually placed on the surface of the graft model. (B) Eigenvectors of the graft and the defect models were oriented to each other until they matched. (C) The defect model was rotated 360° around the axis perpendicular to the articular surface in 1° increments, and least distances of articular surface and resulting subchondral bone surface were calculated at each rotating angle.

ipsilateral and contralateral LFC donors exhibited a significantly larger difference of condylar width between the recipient and the donor than did the MFC donor (ipsilateral LFC donor: 4.06 ± 1.24 mm, $P < .001$; contralateral LFC donor: 3.96 ± 0.62 mm, $P < .001$).

The Mean Least Distance of the Articular Cartilage Surface

The results of the mean least distance of the articular cartilage surface are summarized in Table 2. Comparing the mean least distance of the articular cartilage surface among donor groups, there was no significant difference in the mean least distance in any size at any locations (Fig 6A).Within the MFC donor, the mean least distance of articular cartilage surface increased with increased size. The mean least distance in the 25-mm model was significantly greater than that of the 15-mm model at 0° region ($P = .009$), although there was no significant difference among sizes at 45° posterior and 90° posterior regions. Similarly, the ipsilateral LFC donor and contralateral LFC donor showed that the mean least distance of the articular cartilage surface increased with

Table 2. Descriptive Statistics of the Mean Least Distance of Articular Cartilage Surface Encompassing All Donor − Recipient combinations

	Donor Condyle, mm			
Location and Size	MFC	Ipsilateral LFC	Contralateral LFC	*P* value*
Most distal (0°)				
15 mm	0.273 ± 0.030	0.284 ± 0.041	0.276 ± 0.035	.843
20 mm	0.303 ± 0.042	0.324 ± 0.034	0.304 ± 0.034	.792
25 mm	0.337 ± 0.034	0.389 ± 0.065	0.380 ± 0.063	.209
45° posterior				
15 mm	0.265 ± 0.037	0.270 ± 0.045	0.277 ± 0.050	.890
20 mm	0.313 ± 0.059	0.306 ± 0.042	0.306 ± 0.043	.951
25 mm	0.340 + 0.060	0.349 ± 0.038	0.350 ± 0.043	.667
90° posterior				
15 mm	0.307 ± 0.070	0.307 ± 0.053	0.291 ± 0.063	.814
20 mm	0.350 ± 0.109	0.327 ± 0.051	0.360 ± 0.083	.539
25 mm	0.397 ± 0.150	0.384 ± 0.038	0.436 ± 0.134	.319

NOTE. Data presented as mean ± standard deviation.
MFC, medial distal femoral condyle; LFC, lateral distal femoral condyle.
*Statistical comparison of the mean least distance among donor condyles.

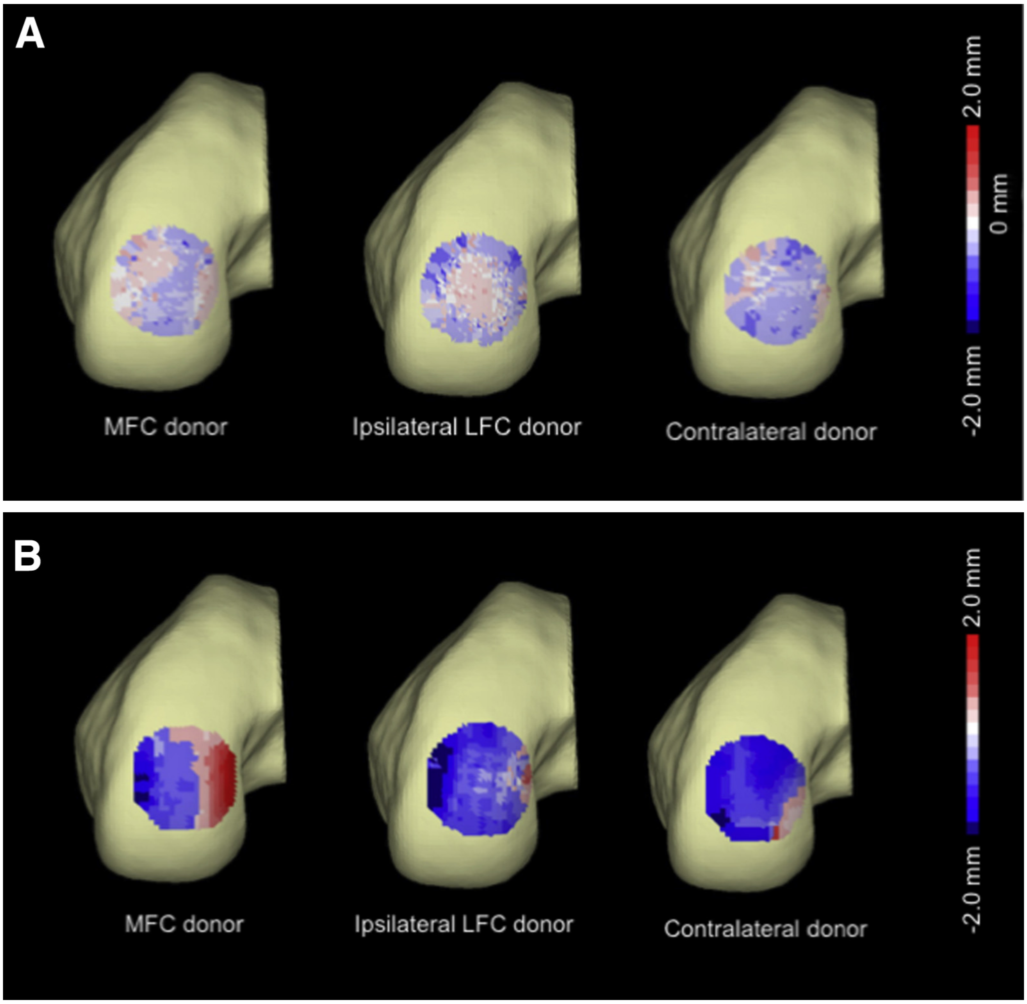

Fig 6. (A) A 3-dimensional representation of the distance distribution of the articular cartilage surface of the 20 mm graft model superimposed on the right medial femoral condyle. The blue gradient color represents penetration into the defect model, whereas red represents prominence. The white color indicates perfect congruence between the defect and the graft models. (B) A 3-dimensional representation of the distance distribution of the resulting subchondral bone surface of the 20 mm graft model superimposed on the right medial femoral condyle. The blue gradient color represents penetration into the defect model, whereas red represents prominence. The white color indicates perfect congruence between the defect and the graft models.

increased size. Within the ipsilateral LFC donor, the mean least distance of the articular cartilage surface in the 25-mm model was significantly greater than that of the 15-mm posterior region models at 0° and 45° ($P = .0027$ and $P = .0025$, respectively) and the 20-mm region model at 0° ($P = .034$). Within the contralateral LFC donor, the mean least distance of the articular cartilage surface in the 25-mm model was significantly greater than that in the 15-mm model regions at 0°, 45° posterior, and 90° posterior ($P = .0019$, $P = .019$, and $P = .0333$, respectively) and that of the 20-mm model region at 0° ($P = .0181$).

The Mean Least Distance of the Subchondral Bone Surface

The results of the mean least distance of the subchondral bone surface are summarized in Table 3. All donor groups exhibited significantly greater mean least distance of the subchondral bone surface than that of the articular cartilage surface ($P < .001$). Comparing the mean least distance of the articular cartilage surface among donor groups, there was no significant difference in the mean least distance of subchondral bone surface in any sizes at any locations (Fig 6B). Although the mean least distance of the subchondral bone surface tended to increase with increased size, there was no significant difference among sizes at any locations within each group.

Discussion

This study investigated the topographic matching of the ipsilateral and contralateral LFC grafts with the MFC defect in 3 different sizes at 3 different locations.

Table 3. Descriptive Statistics of the cMean Least Distance of Subchondral Bone Surface Encompassing All Donor − Recipient combinations

Location and Size	Donor Condyle, mm			
	MFC	Ipsilateral LFC	Contralateral LFC	*P* value*
Most distal (0°)				
15 mm	0.677 ± 0.198	0.725 ± 0.253	0.696 ± 0.207	.871
20 mm	0.737 ± 0.187	0.734 ± 0.170	0.767 ± 0.192	.934
25 mm	0.729 ± 0.195	0.839 ± 0.221	0.811 ± 0.208	.214
45° posterior				
15 mm	0.751 ± 0.238	0.747 ± 0.132	0.717 ± 0.148	.927
20 mm	0.754 ± 0.166	0.769 ± 0.087	0.740 ± 0.109	.914
25 mm	0.783 ± 0.188	0.773 ± 0.092	0.770 ± 0.092	.988
90° posterior				
15 mm	0.660 ± 0.154	0.785 ± 0.086	0.769 ± 0.152	.529
20 mm	0.763 ± 0.148	0.780 ± 0.183	0.726 ± 0.165	.925
25 mm	0.751 ± 0.107	0.896 ± 0.328	0.854 ± 0.230	.522

NOTE. Data presented as mean ± standard deviation.

MFC, medial distal femoral condyle; LFC, lateral distal femoral condyle.

*Statistical comparison of the mean least distance among donor condyles.

Topographic matching of the MFC graft with the MFC defect could be considered as "best efforts" because OCAs are typically ordered from the same side, condyle, and size. Our results showed that the articular cartilage surface matching of the ipsilateral and contralateral LFC grafts for MFC lesions were similar with the MFC graft. Additionally, there was no significant difference in the subchondral bone surface matching among grafts. These suggest that the ipsilateral LFC and contralateral LFCs could be used as OCAs to treat MFC lesions.

The structures of MFCs and LFCs have shown that shape, curvature, and size were different.[13-17] In this study, the condylar width in the LFC donor was greater than that in the MFC recipient. However, these studies were analyzed using the femoral condyle as a whole entity. The surface matching between the graft and recipient should be investigated in each size and location to determine the graft availability of the femoral condyle for osteochondral autograft and allograft transplantation. Previous studies investigated topographic anatomy for osteochondral autografting.[20-26] A few studies, however, focused on topographic matching of the distal femoral condyle for OCA transplantation.[18,19,27]

Mologne et al.[19] investigated the articular cartilage surface match of the LFC to treat the 20-mm MFC defect as OCAs. They showed the overall articular cartilage surface mismatch of 0.63 mm for area and 0.47 mm for step-off, with no significant differences between the MFC and the LFC grafts. Berstein et al.[18] investigated the matching of the radius of curvature of the MFC and LFC grafts with the recipient condyles in 3 zones of the femoral condyle. They showed that the radius of curvature method yielded a higher match rate for lesions than the conventional method, which measures the anterior-posterior and lateral condylar dimensions. These studies suggested that the graft availability of OCA transplantation of femoral condyle could be expanded. Consistent with these findings, our results showed that LFC grafts for MFC lesions yielded similar surface matching with the MFC grafts, indicating the potential use of LFCs to treat MFC lesions as OCAs. One clinical study also demonstrated that non-orthotopic OCA transplantation in the knee provided similar improvement of outcomes of orthotopic OCA transplantation at midterm follow-up.[28]

Some degrees of mismatch can occur, although surgeons attempt to achieve the perfect surface congruence between the graft and the surrounding cartilage. Previous studies showed that the mismatch within 1 mm recession and 0.5 to 1 mm elevation is acceptable.[29-32] Nakagawa et al.[29] showed that the proud plugs provided poor clinical results, but recessing <1 mm promoted acceptable cartilage healing and led to good clinical results. D'Lima et al.[32] showed that grafts proud by 0.5 mm increased peak contact stress by 2 times as large as intact cartilage. Koh et al.[30] demonstrated that peak contact pressure significantly increased with plugs elevated 1.0 and 0.5 mm above the surrounding surface, and that plugs sunk 0.5 and 1.0 mm significantly increased the peak contact pressure in the intact area. The peak contact stress and peak compression strain approached levels that have been shown to induce cartilage damage and cell death.[33,34] The MFC and LFC grafts yielded <0.5 mm of articular cartilage mismatch in this study. These results suggest that the LFC graft for the MFC lesion provide the acceptable biomechanical and clinical results as well as the MFC graft.

The press-fit circular technique is widely used based on the relative ease in achieving a precise graft fit. The diameter of the plug is needed to match with the size of the lesion to provide complete coverage of the affected area. Berstein et al.[18] demonstrated that donor–recipient matches of radius of curvature of the distal femoral condyle decreased with the increased size of lesions. Our study investigated the graft-recipient matching of 3 different sizes (15, 20, and 25 mm) in 3 zones. The articular cartilage surface mismatch increased with increased size, but all mismatch was less than 0.5 mm in all sizes. These suggest that grafts >25 mm may provide >0.5 mm mismatch. However, chondral or osteochondral lesions that are >25 mm are usually larger in the anterior-posterior dimension.[19] Surgeons choose to transplant multiple plugs when the lesion is larger in the anterior-posterior dimension. Based on these, LFC grafts ≤25 mm in size provide the acceptable articular cartilage surface matching in the press-fit circular technique.

The subchondral bone surface mismatch may affect biomechanical properties of the graft and the surrounding cartilage in the recipient. The cartilage thickness is different from MFCs and LFCs and is proportional to the amount of local joint load.[13,35,36] This may cause greater subchondral bone surface mismatch, even if the graft is harvested from LFCs in the same location as the MFC recipient. In this study, the subchondral bone surface matching was investigated when MFCs and LFCs were used as OCAs for the treatment of MFC lesions. Our results interestingly demonstrated that the subchondral bone surface mismatch was greater than the articular cartilage surface mismatch. Furthermore, there was no significant difference in the subchondral bone surface mismatch among MFC, ipsilateral LFC, and contralateral LFC donors. Articular cartilage plays an important role in the distribution of the contact stress within the knee joint.[37] Differences in cartilage stiffness between the graft and the recipient may affect load transmission on the recipient condyle.[38] This suggests that a large subchondral bone surface mismatch causes abnormal stress distribution, which leads to poor clinical results for long-term duration. However, the implication of the subchondral bone surface mismatch, which is greater than the articular cartilage surface mismatch, are yet to be determined. Future consideration will be needed to investigate the effect of subchondral bone mismatch on biomechanical properties and long-term clinical results after OCA transplantation.

The strengths of this study include use of a 3D point-cloud acquisition tool, the efficacy of which has been previously described.[20,39-41] This computer-based computational analysis is based on the determination of the centroid of the femoral hemi-condyle and matching of the orientation of the articular cartilage surface to account for the articular cartilage surface and subchondral bone surface mismatch. Topographic matching is more important than parameters that we recently used to determine the graft availability. Therefore this method may be applied in a clinical setting to determine graft availability. Another strength is that the specimen had no evidence of osteoarthritis because the tissue was procured from a donor tissue bank. This means that our results could provide a true topographic matching for OCA transplantation.

Limitation

There were several limitations in this study. First, this study analyzed topographic matching with single-graft transplantation. Larger lesions in an anteroposterior dimension were required to use 2 to 3 grafts, which is difficult for restoring the curvature of the MFC. Although this study investigated the topographic matching at 3 locations, further investigation is needed to clarify topographic matching when using multiple grafts for larger lesions. Second, the graft and the defect models were created on the center of the femoral condyle in the medial-lateral dimension. The articular cartilage lesion of the MFC such as osteochondritis dissecans is sometimes located on the edge of femoral condyle. In this case, mismatch may be greater than the central lesions because the shape of the edge was different between MFCs and LFCs. Finally, the differences in biomechanical properties between MFCs and LFCs were not investigated. Previous studies showed that the change in tensile integrity of the superficial layer and surface wear occurred at an earlier age in the MFC versus in the LFC.[10] This suggests that the superficial zone in the LFC graft may have better function than the MFC graft.

Conclusion

Ipsilateral and contralateral LFC grafts provide similar articular cartilage surface, resulting in subchondral bone surface that matches that of MFC grafts, suggesting that LFCs could be a potential OCA source for the treatment of MFC lesions.

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