Original Research

Comparison of Initial Stability of Oblong, Large Circular, and Multiple-Plug "Snowman" Osteochondral Autografts for Elongated Focal Cartilage Lesions

A Biomechanical Study in a Porcine Model

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Background: Distal femoral osteochondral allograft transplantation (OAT) is an effective treatment of osteochondral lesions in the knee measuring >2 cm^2 in select patients. Prior studies have demonstrated that the morphology of the plug can affect graft-host interference fit. To our knowledge, there are no data comparing the initial biomechanical stability of standard cylindrical plugs with multiple-plug and oblong-plug morphologies.

Hypothesis: Large cylindrical single-plug (LCSP) and oblong single-plug (OSP) grafts will have greater pull-out strength, and therefore greater initial stability, than multiple-plug (MP) grafts in a cadaveric porcine femur model.

Study Design: Controlled laboratory study.

Methods: A total of 55 porcine distal femurs were divided into 3 groups—LCSP (n = 18), OSP (n = 19), and MP (n = 18)—according to the plug morphology used. The method of graft harvesting and implantation was based on technique guides for the respective implant systems. The sizes (length × width × depth) of the osteochondral defects created in each of the groups were approximately 20.2 × 20.2 × 9.4–mm for the LCSP group, 14.4 × 30.5 × 7.9–mm for the OSP group, and 14.8 × 14.8 × 9.9–mm for the MP group. Tensile testing was performed on each graft to determine pull-out strength.

Results: The pull-out strength was significantly lower in the OSP group (65.7 N) versus the LCSP (133 N; $P = .0005$) and the MP (117.6 N; $P = .001$) groups. There was no statistically significant difference in pull-out strength between the LCSP and MP groups ($P = .42$). There were no statistically significant differences in displacement at maximum load among any 2 of the 3 groups.

Conclusion: These findings suggest that while initial stability may play a role in the clinical outcomes of osteochondral allograft (OCA) implantation, the biological milieu in vivo for each graft setting perhaps has a greater impact on the success of an OAT procedure. Further study is needed on the relationship between OCA biomechanics and clinical outcomes of OAT.

Keywords: osteochondral allograft transplantation; biomechanics; stability; autograft in a porcine model

Osteochondral allograft transplantation (OAT) has been shown to be a reliable and effective method of addressing focal cartilage lesions in the knee measuring >2 cm^2 and in adults typically younger than 50 years.[2] The biomechanical stability of such cylindrical single-plug grafts has been studied using push-in and pull-out models, and the histological response to imperfect graft-host fit has also been characterized.[9] Resistance to pull-out and push-in forces is higher in cylindrical single-plug grafts that are bottomed out, longer, and of greater diameter.[9] Although the increased impaction necessary to insert flush grafts may lead to chondrocyte apoptosis,[12] grafts that are inserted proud demonstrate increased contact forces in vivo as well as fissuring and fibrillation over time.[10] On the other hand, countersunk grafts also demonstrate increased contact forces as well as fibrocartilaginous growth in the recessed area,[10] which may increase susceptibility to degenerative changes, given its biomechanical inferiority to normal hyaline cartilage at opposing joint surfaces.

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Given that most patients indicated for OAT are too young and active for arthroplasty, efforts to increase allograft longevity are crucial. The causes of OAT failure—the need for revision or conversion to unicompartmental or total knee arthroplasty—remain elusive. Clinically, failure has been associated with older patients, those with a greater number of preindex surgical procedures on the same knee, and those with a higher body mass index or a bipolar lesion.[6,7] Histologically, grafts retrieved during revision surgeries show fibrocartilage deposition interrupting the host-graft interface, with chondrocyte viability and osteocyte viability diminished in early and late failure, respectively.[8] Furthermore, subchondral instability via microfractures from increased degeneration increases the risk of scar tissue production and nonunion. Mechanical stability in the graft is key and requires the host bone to replace the graft bone. For larger defects, maintenance of this stability for successful graft inclusion can become more challenging with the need to use multiple plugs or larger, oval-shaped grafts.

The biomechanical stability of multiple-plug, "snowman" technique grafts used to treat oblong defects is not as well known. Similarly, the stability of newer single-plug oblong grafts has also not been characterized. A recent study reporting the midterm outcomes of patients receiving multiple-plug grafts found a 44.4% risk of reoperation and a 33.3% risk of failure, which is significantly higher than that reported for cylindrical single-plug grafts at even a longer follow-up.[4] This difference may be partially because of inferior biomechanical stability of multiple-plug (MP) grafts.

The aim of this study was to measure and compare the forces required to displace large cylindrical single-plug (LCSP) grafts, oblong single-plug (OSP) autografts, and MP autografts in porcine distal femurs using a pull-out experimental setup. We hypothesized that LCSP and OSP grafts would require an increased tensile force to displace them compared with MP grafts in a porcine cadaveric knee model. The rationale for use of pull-out strength as the primary measure was that pull-out strength is likely related to interference at the implant-bone interface, and the degree of interference is known to affect micromotion, which in turn affects osseointegration.[1] Elucidating the stability of these various graft morphologies will develop the current paucity of the literature regarding graft shapes and assist clinicians in graft selection for patients undergoing OAT procedures.

METHODS

Study Design

This study used 60 porcine cadaveric distal femurs stripped of all soft tissue. The Osteochondral Autograft Transplantation System (OATS) and the BioUni OATS System (Arthrex) were used to harvest and implant grafts in each group. In the LCSP group, a 20–mm diameter × 9.810–mm thick osteochondral graft was harvested from the medial condyle and implanted in the corresponding location of the lateral condyle. In the MP group, three 15–mm diameter × 9.410–mm thick osteochondral plugs were harvested from 1 condyle and trochlea and implanted in the other condyle in an overlapping configuration to cover an area 30 mm in length. In the OSP group, an elliptical osteochondral graft with central height of 10 mm, base length of 30.2 mm, and central width of 14.25 mm was harvested from 1 condyle and implanted in the corresponding location of the other condyle. All grafts were harvested to an intended depth of 10 mm. Two grafts each in the MP and LCSP groups and 1 graft in the OSP group were rendered unusable during the harvesting process, leaving 55 final specimens: 18, 18, and 19 in the MP, LCSP, and OSP groups, respectively.

The length, width, and depth of all plugs and recipient beds were measured with a metal ruler and recorded. All plugs were gently tamped into place by hand, as described in the technique guides for both OATSs. Table 1 shows the dimensions of all plugs and beds. Figures 1A and 1B demonstrate the morphology of grafts in the OSP and MP groups, respectively.

Tensile testing was performed on grafts after transplantation using a tensile test machine (MTS Systems Corp). Each specimen was prepared for testing by inserting a 2-mm screw eye into the center of the plug to an approximate depth of 5 mm without violating the bony surface of the graft. In the MP group, the circular end plug within the multi-plug configuration was chosen as the location of the screw eye (Figure 1C). The screw was further secured with 2 to 3 drops of thread-locking compound (Threadlocker Blue 242; Loctite) to avoid failure at the screw-graft interface. Specimens were then fixed in an upright orientation in the tensile test machine. A load perpendicular to the articular surface was applied at a rate of 10 mm displacement/minute—the rate chosen based on the methodology from prior studies[3,5]—and force-displacement curves were generated to determine pull-out strength (maximum load in newtons) and displacement at maximum load.

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Ethical approval was not sought for the present study.

Statistical Analysis

All data were imported into SAS Version 9.4 (SAS Institute Inc) for data management and analysis. Regression models were used to compare the maximum load and the displacement at maximum load. The displacement at maximum load was logarithmically transformed to satisfy the assumptions of linear regression. The maximum likelihood estimators of the model were adjusted for possible model misspecification using classical sandwich estimators. Separate models were run for each outcome. Post hoc pairwise comparisons between types (LCSP, OSP, and MP) were conducted via orthogonal contrasts. The Holm test was used for multiple comparisons to maintain a 2-tailed family-wise alpha at .05. All modeling was completed using the PROC GLIMMIX procedure, and all post hoc pairwise comparisons were completed using the LSMEANS statement. All estimates were reported as mean values along with their 95% CIs. $P < .05$ was used to determine statistical significance.

Any discrepancy between the plug and recipient bed dimensions was also analyzed. Pearson correlation coefficients were calculated to examine the correlation between the maximum load and the displacement at maximum load and the discrepancy between the bed and the plug diameter. The discrepancy was calculated as the diameter of the bed minus the diameter of the plug for the correlation analysis. Regression models were used to examine whether the maximum load and the displacement at maximum load were associated with the presence of a discrepancy between the bed and the plug size. The slope of the regression line (B) and the standard error (SE) of this value were reported. Interaction terms between discrepancy and type (LCSP, MP, and OSP) were added to the regression model to see whether the relationship between force measures and discrepancies differed by type. $P < .05$ was used to determine statistical significance.

TABLE 1
Dimensions for LCSP, MP, and OSP Plugs and Beds[a]

	Width, mm	Length, mm	Depth/Thickness, mm
LCSP			
Plug	20	20	9.8
Bed	20.2	20.2	9.4
MP			
Plug	15	15.1	9.4
Bed	14.8	14.8	9.9
OSP[b]			
Plug	14.2	30.2	12-o'clock: 7.7 3-o'clock: 10.4 6-o'clock: 8.2 9-o'clock: 10.3
Bed	14.4	30.5	12-o'clock: 6.5 3-o'clock: 9.8 6-o'clock: 5.9 9-o'clock: 9.4

[a]Values are reported as mean values without standard deviation for ease of visualization. LCSP, large cylindrical single plug; MP, multiple-plug; OSP, oblong single-plug.

[b]Thicknesses of the OSP plug and beds were measured in all 4 directions (given as clockface positions).

RESULTS

Table 1 displays the mean dimensions for all plugs and beds. Figure 2 and Table 2 display the estimated maximum load and displacement at maximum load for each allograft type. The maximum load was significantly lower in the OSP group compared with the LCSP group (65.7 vs 133 N, respectively; $t = 4.05$; $P = .0005$) and the MP group (65.7 vs 117.6 N; $t = 3.72$; $P = .001$). There was no statistically significant difference in maximum load between the LCSP and MP groups ($P = .42$). The displacement at maximum load trended lower in the OSP group compared with the LCSP group but did not reach statistical significance (0.44 vs 0.71 mm, respectively; $t = 2.42$; $P = .058$). There were no statistically significant differences in displacement at maximum load between the LCSP and MP groups ($P = .45$) nor between the MP and OSP groups ($P = .28$).

The results of the Pearson correlation coefficient analysis are shown in Table 3. Maximum load ($R = 0.06$, $P = 0.67$ and $R = -0.03$, $P = 0.84$) and displacement at maximum load ($R = -0.18$, $P = 0.21$ and $R = -0.12$, $P = 0.40$) were not correlated with discrepancy between bed and plug diameter

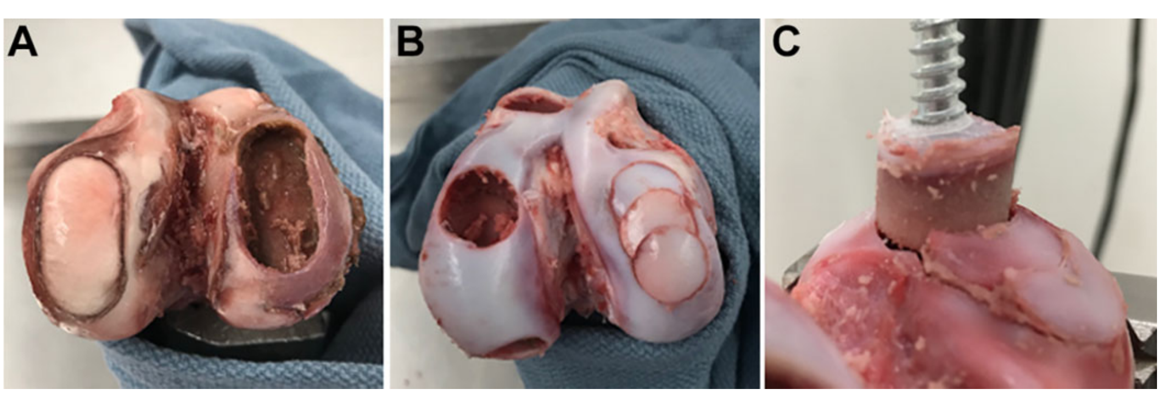

Figure 1. Morphology of grafts for (A) the OSP and (B) MP grafts. (C) Position of the screw-eye in the multiple-graft configuration. This image also demonstrates the end state of the graft after tensile testing. MP, multiple-plug; OSP, oblong single-plug.

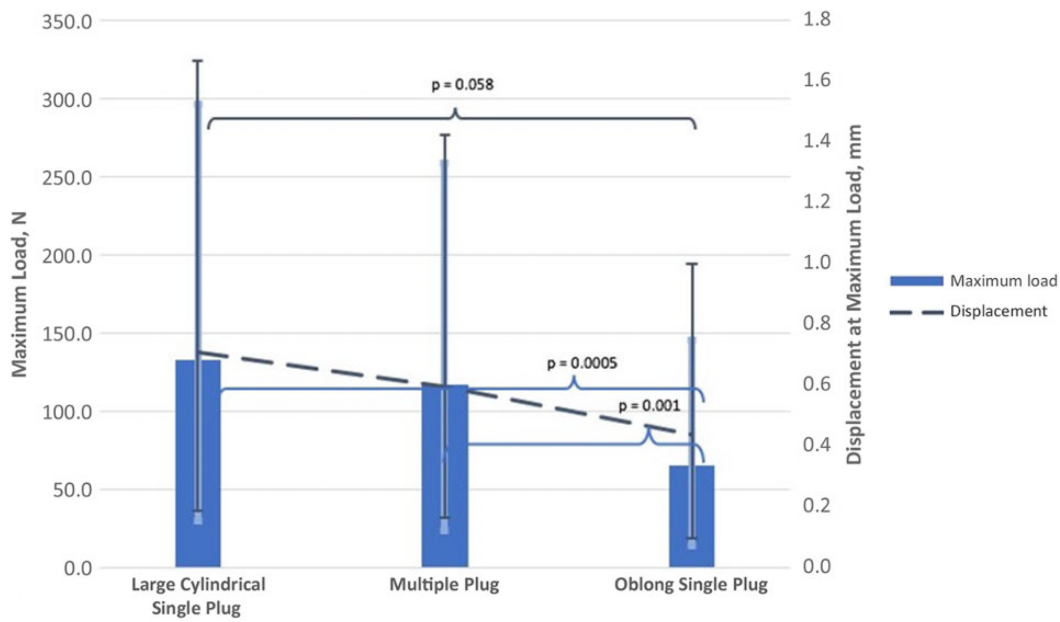

Figure 2. Maximal tensile force needed to induce failure of all 3 graft morphologies and the displacement of the graft at this failure threshold.

TABLE 2
Estimated Maximum Load and Displacement at Maximum Load[a]

Group	Maximum Load, N	Displacement at Maximum Load, mm
LCSP (n = 18)	133 (102.9-163.2)	0.71 (0.52-0.96)
MP (n = 18)	117.6 (93.6-141.6)	0.60 (0.43-0.83)
OSP (n = 19)	65.7 (51.3-80.1)	0.44 (0.34-0.56)

[a]Estimates are reported as mean (95% CI); LCSP and MP each have 1 missing value because of the screw pull-out. LCSP, large cylindrical single-plug; MP, multipleplug; OSP, oblong single-plug.

(Table 3). In a separate analysis, regression models showed that there was no significant association between maximum load and the presence of a discrepancy between bed and plug size (diameter 1: B = 4.75, SE = 18.49, $P = 0.80$ and diameter 2: B = −6.82, SE = 36.03, $P = 0.85$). The relationship between maximum load and discrepancy did not differ by type ($P = 0.59$ for diameter 1 and $P = 0.70$ for diameter 2). Regression models also showed that there was no significant association between displacement at maximum load and presence of discrepancy between bed and plug size (diameter 1: B = −0.01, SE = 0.13, $P = 0.92$ and diameter 2: B = −0.12, SE = 0.28, $P = 0.69$). The relationship between displacement at maximum load and discrepancy did not differ by type ($P = 0.11$ for diameter 1 and $P = 0.20$ for diameter 2).

DISCUSSION

When using OAT techniques, the choice of graft configuration has significant implications for graft stability and patient outcomes overall. The present study was designed to compare the pull-out forces required to displace LCSP, OSP, and MP osteochondral allograft (OCA) plug grafts in a porcine knee model. Our key finding was that the pull-out strength of the OSP group was significantly less than that of both the LCSP and MP configurations, and there was no significant difference in pull-out strength between the LCSP and MP groups. Less importantly, the displacement at the maximum load in the OSP trended lower when compared with the LCSP; however, there were no statistically significant differences in displacement at maximum load among the 3 graft morphologies. This serves as an internal control for our study and indicates that there was likely no significant difference in the calibration of actuators between groups. Importantly, there was no association between graft pull-out strength and the degree of discrepancy between the graft and defect dimensions.

In a case series, Cotter et al[4] compared snowman (n = 9) and multifocal (n = 15) OAT configurations for large chondral lesions and discontinuous lesions in multiple compartments, respectively. They highlighted that patients in the snowman group experienced improvement in midterm clinical outcomes (per the Knee Injury and Osteoarthritis Outcome Score, Western Ontario and McMaster Universities Arthritis Index, and 12-Item Short Form Health Survey). However, ultimately, they had high rates of reoperation (44.4%) and failure (33.3%) compared with the multifocal group. Importantly, the multifocal group included patients who received multiple cylindrical single plugs that were not overlapped, yet they showed superior reoperation and failure rates (20% and 6.7%, respectively). In essence, Cotter et al[4] demonstrated that overlapping grafts may be associated with poorer clinical outcomes than nonoverlapping grafts. However, this conclusion was drawn based on

TABLE 3
Pearson Correlation Coefficients Between Maximum Load and Displacement With Bed-Plug Discrepancy[a]

	Maximum Load	Displacement	Discrepancy: Diameter 1	Discrepancy: Diameter 2
Maximum load	1			
Displacement	—	1		
Discrepancy: diameter 1	0.06 (P = .67)	–0.18 (P = .21)	1	
Discrepancy: diameter 2	–0.03 (P = .84)	–0.12 (P = .40)	—	1

[a]—, no value to report.

osteochondral lesions in 2 groups that were not morphologically the same.

Although the results of the present study did not reveal a significant difference in pull-out strength between the LCSP and MP configurations, they do not necessarily refute the conclusions of the study by Cotter et al.[4] A possible explanation for similar initial graft stability yet worse clinical outcomes may be found in the in vivo versus ex vivo contexts of these 2 sets of results. While both graft configurations may begin with a similar stability profile at the time of transplantation, the biological integration of the grafts and the effects of the mechanical load may have a greater destabilizing effect on an MP arrangement compared with that of an LCSP graft. This may be attributable to the fact that the entire circumference of the LCSP is supported by the fixed defect created during bed preparation, whereas the largest graft of the MP arrangement is partially dependent on its neighboring plugs for stability. Ultimately, a weak link in the snowman configuration may lead to eventual destabilization of the entire graft. It is important to know that our experimental setup involved applying tension only to the circular plug at the base of the MP configuration. The crescentic portions of the configuration may have demonstrated lower pull-out strength.

While circular plugs have been well studied and characterized, the same cannot be said about oblong-shaped grafts. Large ovoid chondral lesions have historically been treated with multiple circular grafts in which multiple graft-graft and graft–native bone interfaces are created to fill the defect. New oblong OATSs seek to circumvent this pitfall and afford a single continuous interface between the graft and receiving bone, which may help overcome some of the failures of the snowman technique. A study published in July 2020 by Urita et al[11] used 3-dimensional computer simulation models to analyze the topographical matching of oblong OCAs to large oval-shaped chondral lesions in the medial distal femoral condyle (MFC). Two defect sizes in the MFC were assessed: 17 × 30–mm and 20 × 30–mm. The best graft-to-lesion match was achieved using oval grafts from the MFC that had articular cartilage surface mismatch and peripheral step-off of no more than 0.5 mm for both defect sizes. That study demonstrated the feasibility of obtaining an oblong graft to accurately fill an ovoid defect but did not address the biomechanical stability thereof.

Despite the theoretical benefits of an oblong-shaped plug, our present study demonstrated significantly weaker pull-out strength in the OSP group (15 × 30–mm) compared with both the LCSP and MP groups, and this is a finding that, to our knowledge, has not previously been demonstrated. Although poor congruity between the defect and the graft (ie, the graft was smaller than the defect) could explain this result, there was no statistically significant mismatch between the graft and defect diameters in the OSP group, and the diameter differences did not account for the decreased load to failure for this group. Decreased initial stability with the OSP morphology is an interesting finding that warrants further study, especially in the context of ideal graft-to-lesion match per the study of Urita et al.[11]

There are several limitations to the present study. First, this biomechanical study evaluated initial OCA stability by evaluating the maximum load to failure caused by a pull-out force. While initial pull-out strength may be a reasonable way to assess how well a graft is fixed in its associated defect, it does not test the graft-defect interface in a push-in or shear fashion that is more representative of true biomechanics at the knee. Another limitation is that the reported displacement at maximum load includes actuator displacement and, as such, may not represent the true displacement of the graft itself during tensile testing. Also, the vector of tensile force application was not controlled rigidly between samples. Although a best effort was made to align each distal femur with the actuator in the same way, an apparatus to rigidly ensure this was not constructed, which may also have contributed to the error in our results. These errors are likely evenly distributed between each graft group, however.

Another limitation is that the stability of the MP or the snowman configuration was measured based on the strength of the largest graft in the arrangement (ie, the base of the snowman). However, stability of this graft arrangement may be affected by the stability in the adjacent grafts in the MP mosaic, which may better represent the reason for failure in this graft configuration. In addition, the radius of curvature of the porcine knee model used in this study is smaller than that of the adult human knee. As such, the geometries and associated graft-defect interfaces evaluated in this study could potentially produce different results when applied to a distal femur model with a radius of curvature that more closely represents that of the adult human knee.

Last, our study only assesses initial graft stability. Given that failures occur several years into transplantation, the experiment may not have captured the accurate environment to assess graft success or failure. Nevertheless, this study is among the first to assess oblong OCA stability and may help inform orthopaedic surgeons in deciding which graft morphologies to use for an elongated cartilage defect, which in turn may lead to improved outcomes in patients undergoing OAT. While it is difficult to provide a recommendation for clinicians treating oblong distal femoral osteochondral lesions based on this cadaveric porcine model, the present study demonstrates that perhaps greater initial stability can be achieved by avoiding the use of a single oblong osteochondral graft.

CONCLUSION

In patients with osteochondral defects of the knee that are treatable with OAT, careful consideration by the operating surgeon of graft morphology and stability can lead to better patient outcomes. The large cylindrical graft showed the highest pull-out strength, with significantly higher forces required for pull-out over the oblong graft. Furthermore, pull-out strength was significantly weaker in the oblong grafts compared with the LCSP and MP grafts, demonstrating its inferior initial stability in this cadaveric porcine model. There were no significant findings regarding displacement at failure among the groups, nor were there any significant associations between pull-out strength and discrepancy between the bed and plug dimensions for any graft morphology. The present study adds meaningful biomechanical information about newer, oblong grafts while complementing the existing and growing literature on clinical outcomes of the snowman configuration so that operating surgeons can be better informed about their OCA choices.

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