An Innovative Approach to Concave-Convex Allograft Junctions: A Biomechanical Study

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Abstract

Allograft bone is often used in oncologic and trauma limb salvage procedures. In this study, we hypothesize that a concave-convex allograft junction with plate fixation would improve multiple aspects of the reconstruction process, allowing for a larger contact surface area between the allograft junction and increased uniformity in pressure distribution at the junction.

Thirty large femoral artificial polyresin femurs were randomly separated into 2 groups: allograft junctions fixed with flat locking plates and allograft junctions fixed with prebent locking plates. Each group was then randomly subdivided into 3 sets: concave-convex allograft junctions, matched transverse-cut allograft junction, and non-matched transverse-cut allograft junctions.

All but 1 reconstructions of concave-convex allograft junctions, compared with non-matched or matched transverse-cut allograft junctions fixed with flat or pre-bent locking plates showed statistically significant greater mean contact surface area and greater mean percent contact surface area (*P*<.05). Concave-convex allograft junctions demonstrated increased mean contact surface area, mean percent contact surface area, and a more uniform pressure distribution.

We believe our approach to allograft junctions using concave-convex reamers may improve multiple aspects of the reconstruction process, allowing for increased contact surface area between the allograft junction, increased uniformity in pressure distributions at the allograft junction, and decreased length of time taken for intraoperative preparation.

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Allograft bone is often used in oncologic and trauma limb salvage procedures. Approximately 150,000 musculoskeletal large segmental allograft procedures are performed each year in the United States.[1] With recent advances in diagnostic technology, adjuvant therapy, and surgical treatment, limb salvage continues to be performed more often than amputative surgery. In cases in which a tumor is located in a diaphyseal segment of bone, intercalary allograft reconstruction allows limb salvage surgery to be performed without involving the articular surface.

Although tumor resection with allograft transplantation is the limb salvage procedure often preferred in intercalary reconstructions, these reconstructions are not without complications. The most common mechanical complication is nonunion at the allograft–host junction. Nonunion is defined clinically as an osteosynthesis site that is not radiographically united 12 months after surgery.[2] Intercalary host–graft nonunion rates reported in the literature have ranged widely, from 5% to 49%.[3-5] For these junctions, mean time to union has been reported to be approximately 8 months, with 4 months for cancellous-cancellous junctions and 12 months for cortical-cortical junctions.[5] Several factors affect graft-host healing, including patient nutritional status, adequacy of soft-tissue coverage, exposure to chemotherapy or radiation, and infection. In particular, in a study of 73 cadaveric allograft retrievals, Enneking and Campanacci[5] noted that accurate intimate contact at the osteotomy site appears to promote and accelerate union. Their observations emphasize the importance of construct stability, host-graft contact area, and uniformity of pressure distribution across the construct.

We believe that our proposed technique of concave-convex reaming of allograft-host junctions allows for a larger contact surface area of bone, thus theoretically increasing healing. Investigators have studied different configurations as means of improving the union rates at allograft junctions as well as implementation of transverse-cut, step-cut, and sigmoid osteotomies. A limitation of these techniques is that, once a cut is made, rotation cannot be altered at these junctions.

Bargiotas and colleagues[6] reported enhanced bone-healing, fewer complications, and lower reoperation rates in their population of patients with knee arthrodeses when the

Table I. Measured Contact Surface Area, Compared With Potential Surface Area, mm^2

Set No.	Fixation Method	Cut Type, Junction Type	Surface Area, mm^2 Measured Mean	Measured SD	Potential Mean	Potential SD	Contact Surface Area, %
1	Flat plate	Concave–convex allograft junction	335.84	68.58	840.4	55.11	39.80
2	Flat plate	Matched transverse-cut junction	136.04	18.69	686.6	37.84	19.90
3	Flat plate	Nonmatched transverse-cut junction	123.18	45.89	670.4	31.45	18.29
4	Prebent plate	Concave–convex allograft junction	343.28	76.94	787.2	56.50	43.50
5	Prebent plate	Matched transverse-cut junction	215.66	38.45	681.4	27.95	31.60
6	Prebent plate	Nonmatched transverse-cut junction	155.84	25.49	713.0	26.99	21.80

Table II. Unpaired t Test Analysis of Concave-Convex Allograft Junctions, Compared With All Other Allograft Junctions[a]

Concave–Convex Junction Fixation Method	Other Allograft Junctions and Fixation Methods	*P*
Flat plate	Matched transverse-cut junction with flat plate	.0003
Flat plate	Nonmatched transverse-cut junction with flat plate	.0009
Flat plate	Matched transverse-cut junction with prebent plate	.0617
Flat plate	Nonmatched transverse-cut junction with prebent plate	.0006
Prebent plate	Matched transverse-cut junction with flat plate	.0004
Prebent plate	Nonmatched transverse-cut junction with flat plate	.0007
Prebent plate	Matched transverse-cut junction with prebent plate	.0275
Prebent plate	Nonmatched transverse-cut junction with prebent plate	.0006

[a] 95% confidence interval.

proximal and distal ends were prepared in a ball-and-socket fashion as opposed to a parallel approach. Their study led us to expect similar results when using intercalary reamed concave-convex allograft junctions after tumor resection. To our knowledge, no one has compared concave-convex allograft junctions with current operative procedures using straight osteotomy junctions in limb salvage surgery.

In the study reported here, we hypothesized that a concave-convex allograft junction with plate fixation would improve multiple aspects of the reconstruction process, allowing for a larger contact surface area between the allograft junction and increased uniformity in pressure distribution at the junction.

MATERIALS AND METHODS

Thirty large femoral artificial polyresin femur models (biomechanical sawbone specimens; Sawbones, Vashon, Washington) were randomly divided into 2 groups to compare the experimental allograft-host junctions at the midshaft of the diaphysis of each femur. Group 1 (n = 15) consisted of various allograft-host junctions fixed with flat locking plates, and group 2 (n = 15) consisted of various allograft-host junctions fixed with prebent locking plates.

The 15 samples in group 1 were randomly subdivided into three 5-sample sets: concave-convex allograft junctions, matched transverse-cut allograft junctions, and nonmatched transverse-cut allograft junctions. Set 1 samples were transected perpendicularly and then shaped with a commercially available concave-convex reamer to obtain a ball-and-socket configuration (Figures 1A, 1B). The concave-convex reamer is used clinically to prepare the acetabulum and femoral head in hip resurfacing. The respective proximal and distal ends were then reassembled in proper anatomical align-

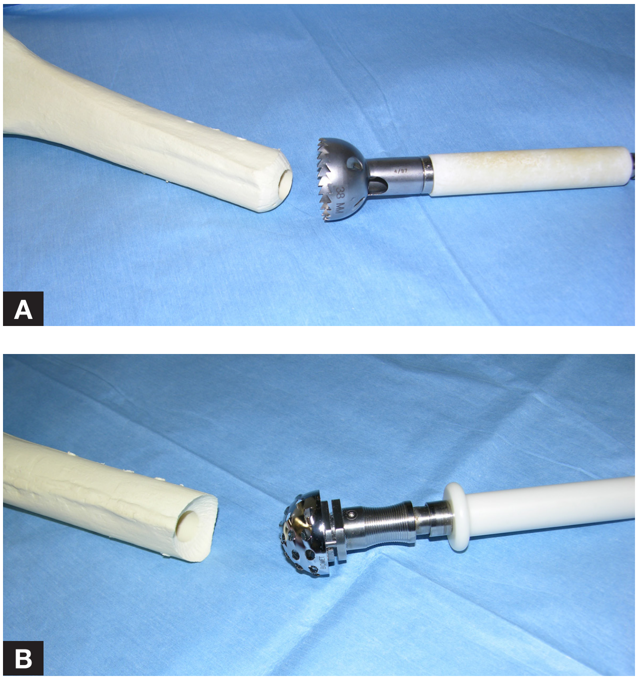

Figure 1. (A) Concave reamer used to make convex junction in allograft. (B) Convex reamer used to make concave junction in allograft.

Table III. Unpaired t Test Analysis of Flat Versus Prebent Plates With Same Type of Allograft Junction[a]

Junction Type	*P*
Concave-convex	.4634
Matched transverse-cut	.0024
Nonmatched transverse-cut	.3093

[a] 95% confidence interval.

ment (Figure 2). Set 2 samples were manually transected perpendicularly at the midshaft. The transected respective proximal and distal ends were then reassembled in proper anatomical alignment. Set 3 samples were prepared in the same fashion as set 2 samples, but then the transected proximal midshaft ends were randomly assigned to other distal ends before realignment. All group 1 samples were stabilized with a 10-hole flat locking compression plate (Synthes, West Chester, Pennsylvania).

The 15 samples in group 2 were subdivided into 3 sets in the same fashion as group 1 but were then stabilized with a 10-hole prebent locking compression plate (Synthes; Figure 3).

Before the 2 ends were fixed and joined, a piece of Pressurex Super Low Film (Sensor Products, Madison, New Jersey) was placed at each allograft–host junction to measure the contact surface area (Figures 4, 5). This Mylar-based film has a layer of microcapsules. Applying pressure to the film causes these microcapsules to rupture, leaving a permanent, high-resolution red topographic image that reflects the areas of contact. In addition, pressure variations are indicated by different color intensities, with higher pressures marked by darker reds. The cut edges of the distal segment were traced to estimate the total potential contact surface area of each sample, as indicated in blue (Figures 6A, 6B).

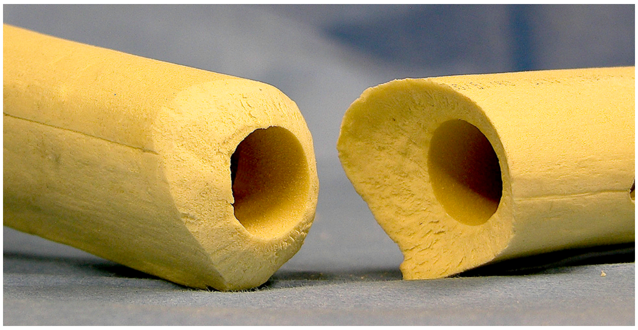

Figure 2. Allograft junction with concave-convex configuration.

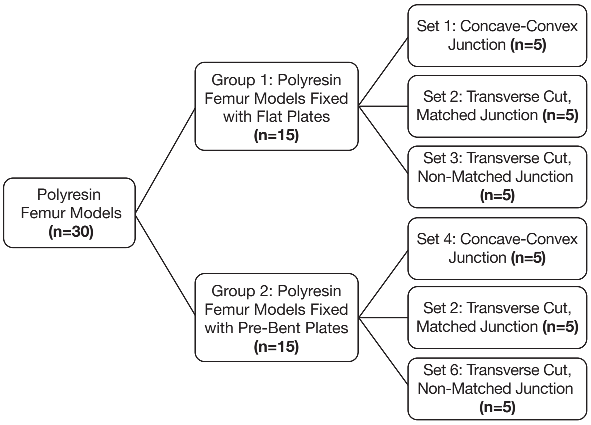

Figure 3. Flow chart of allograft distribution method; n is the number of allograft samples.

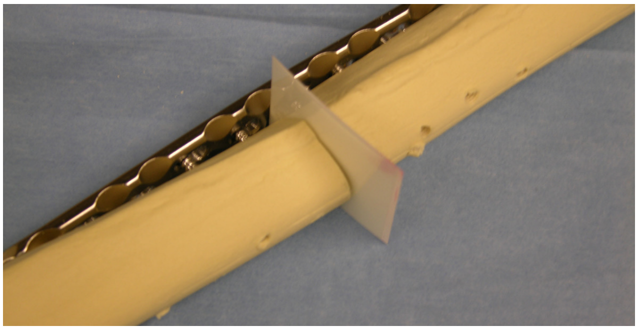

Figure 4. Matched transverse-cut allograft junction with flat plate before fixation. Pressurex Super Low Film (Sensor Products, Madison, New Jersey) was placed between junction.

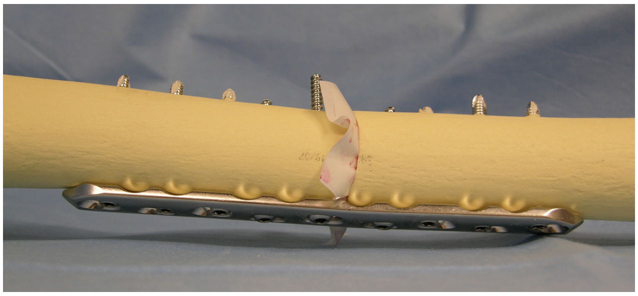

Figure 5. Concave-convex allograft junction fixed with flat plate.

After the 3 sets of samples were prepared, allograft junctions were separated and Pressurex film removed. Total potential contact surface area was measured using the outlined edges of the proximal bone from the film. The film was then analyzed by uploading the corresponding Pressurex digital picture to the SigmaScan digital software (Systat Software, San Jose, California). The topographic image of red pixels was analyzed so that total contact surface area could be calculated; this area was then divided by total potential contact surface area to determine percent contact surface area (Table I). In addition, red pixel distribution was qualitatively analyzed to compare the pressure distribution of the allograft junctions.

Unpaired *t* test analysis at 95% confidence intervals (CIs) was performed on percent contact surface area to compare concave-convex allograft junctions with matched and nonmatched transverse-cut allograft junctions (Table II). In addition, separate unpaired *t* test analyses at 95% CIs were performed on percent contact surface area to compare flat and prebent plates in each allograft junction configuration (Table III).

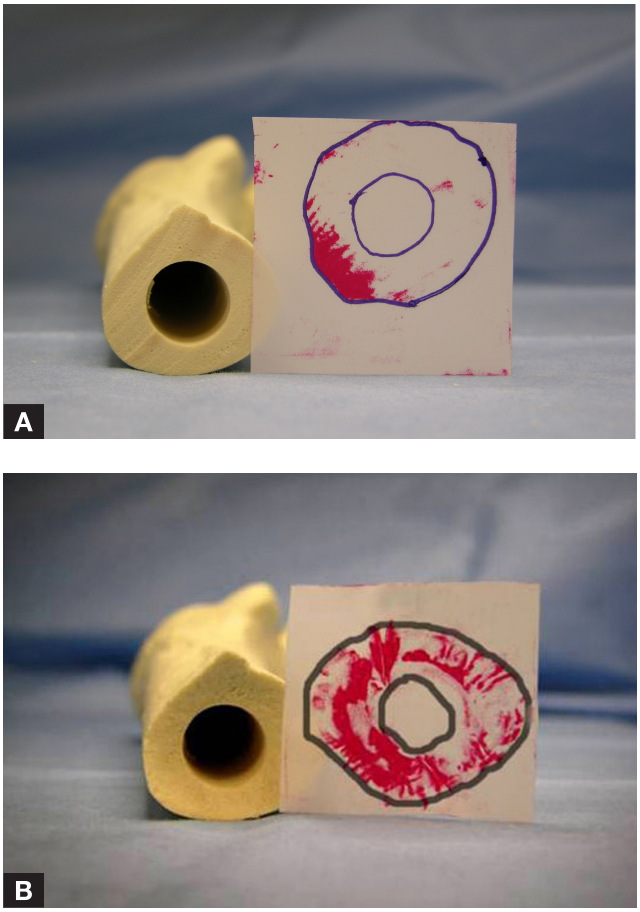

Figure 6. (A) Pressurex film shows unequal pressure distribution in matched traverse-cut allograft junction fixed with flat plate. (B) Pressurex film shows more uniform pressure distribution in concave-convex allograft junction fixed with flat plate.

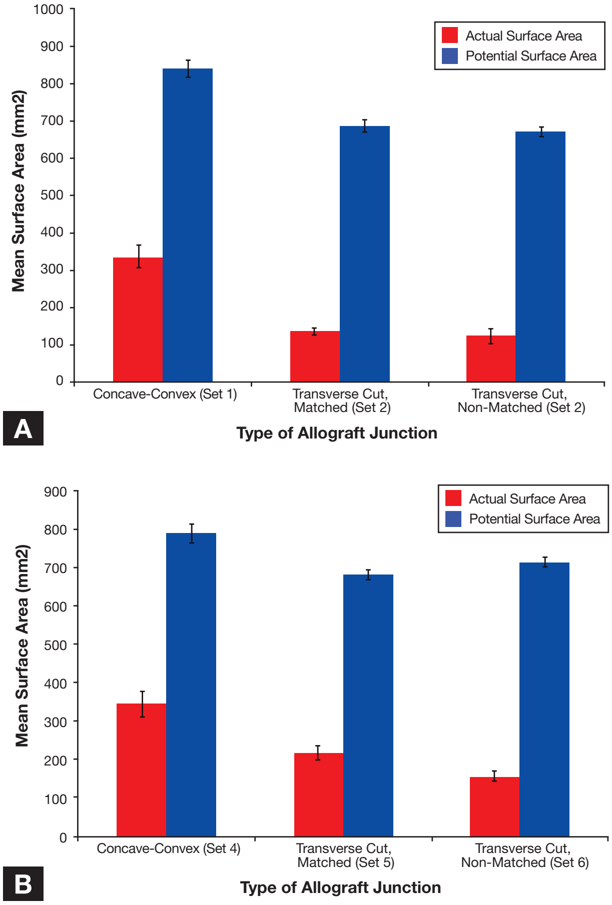

Figure 7. Comparison of mean contact surface area and mean potential contact surface area of allograft junctions fixed with flat (A) and prebent (B) plates.

RESULTS

Mean contact surface areas for femora with concave–convex allograft junctions (set 1), matched transverse-cut allograft junctions (set 2), and nonmatched transverse-cut allograft junctions (set 3) stabilized with flat locking plates (group 1) were 335.84 mm^2, 136.04 mm^2, and 123.18 mm^2, respectively. Mean percent contact surface areas of sets 1, 2, and 3 were 39.8%, 19.9%, and 18.3%, respectively (Table I).

Mean contact surface areas for femora with concave-convex allograft junctions (set 4), matched transverse-cut allograft junctions (set 5), and nonmatched transverse-cut allograft junctions (set 6) stabilized with prebent locking plates (group 2) were 343.28 mm^2, 215.66 mm^2, and 155.84 mm^2, respectively. Mean percent contact surface areas of sets 4, 5, and 6 were 43.5%, 31.6%, and 21.8%, respectively (Table I).

Femora reconstructed with concave-convex allograft junctions showed a larger mean contact surface area (Figures 7A, 7B) and a larger mean percent contact surface area when individually compared with femora reconstructed with either matched or nonmatched transverse-cut allograft junctions fixed with flat or prebent locking plates (Figures 8A, 8B). Table II shows the unpaired *t* test analysis of the mean percent contact surface area of the concave–convex allograft junctions (sets 1, 4), compared with the other transverse-cut allograft configurations (sets 2, 3, 5, 6). The unpaired *t* test analysis of the mean percent contact surface area of the concave-convex allograft junctions fixed with flat plates and the matched transverse-cut allograft junctions fixed with prebent plates was not statistically significant ($P = .0617$). Statistical significance was found for all other samples when mean percent contact surface area of concave–convex allograft junctions was compared with that of the other tested sets (95% CI, $P<.05$; Table II).

Data for the flat and prebent locking plates of the same allograft junction were analyzed as well (Table III). Concave-convex allograft junctions fixed with flat plates (set 1) and prebent plates (set 4) were not statistically different ($P = .4634$). Mean percent contact surface area was statistically significantly ($P<.0024$) larger for matched transverse-cut allograft junctions fixed with prebent plates (set 5) than for those fixed with flat plates (set 2). Nonmatched transverse-cut allograft junctions fixed with flat plates (set 3) and prebent plates (set 6) were not statistically significantly different ($P = .3093$).

The Pressurex films of the proximal portions of matched transverse-cut junctions fixed with flat plates (set 2) and concave-convex allograft junctions fixed with flat plates (set 1)

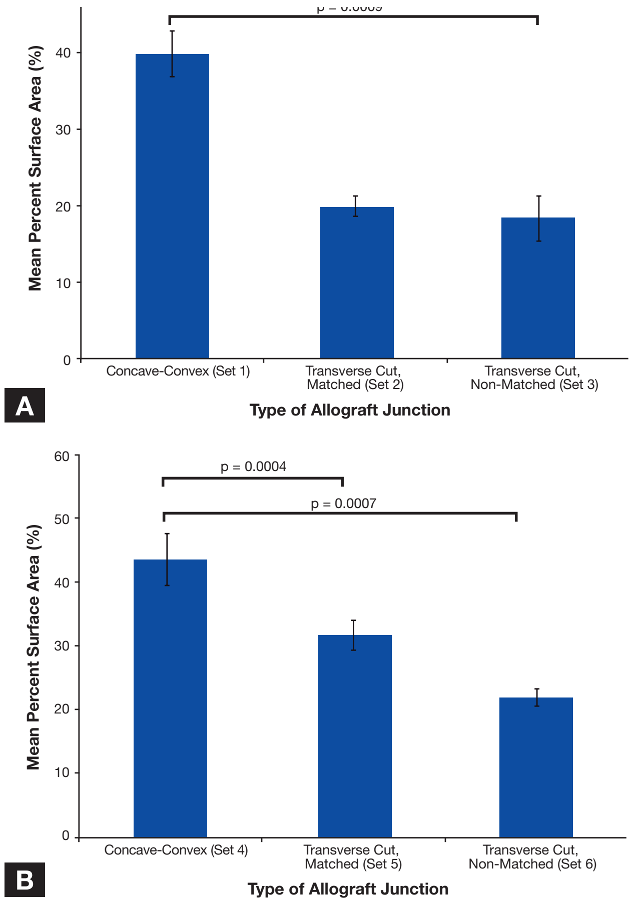

Figure 8. (A) Comparison between mean percent contact surface area of concave–convex allograft junction fixed with flat plate and matched and nonmatched transverse-cut allograft junctions fixed with flat plate. (B) Comparison between mean percent contact surface area of concave–convex allograft junction fixed with prebent plate and matched and nonmatched transverse-cut allograft junctions fixed with prebent plate.

are shown in Figures 4 and 5, respectively. More pressure was applied (darker red), and pressure distribution was more uniform, with concave-convex allograft junctions.

DISCUSSION

Placement of a cadaveric segmental allograft is the preferred method for skeletal reconstruction after tumor resection in the diaphyseal segment of a bone, but it carries a high nonunion rate, and nonunion may lead to further complications and morbidities, including loss of mobility and need for reoperation. Infection and other comorbidities are factors in nonunion rates. Another is allograft configuration, which affects the contact surface area between the allograft junction, the distribution of pressure at the allograft junction, and the time needed for intraoperative preparation.

In our study, contact surface area is best described as the amount of surface of a free bone edge in contact with an opposing free edge. Maximizing the contact surface area in allograft junctions has been found to increase bone healing.[7,8] McGrath and colleagues[9] proposed that using end-cutting intramedullary reamers to enlarge the surface area at the allograft junction can lower the rate of nonunion of allograft junctions, though they did not present any biomechanical or clinical evidence. According to Enneking and Campanacci,[5] accurate and intimate allograft junctions allow for promotion and acceleration of bone healing at union sites. They noted that fixation security, as well as degree of contact, affected the size and the extent of the external callus and the maturation into haversian bone.

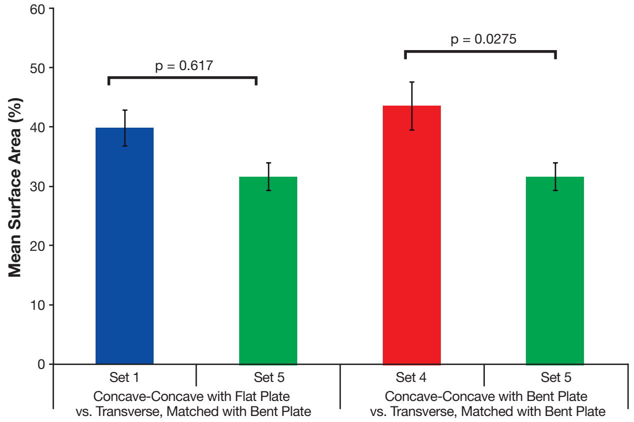

Figure 9. Comparison between gold-standard matched transverse-cut allograft junction fixed with prebent plate and both concave-convex allograft junction configurations.

One common method of allograft junction fixation involves locking compression plates. A locking compression plate may be used as a compression plate, a locked internal fixator, or both. These plates are versatile in that they allow for a single fixation system to be adapted to the needs of each particular patient.[10] Junction stability and healing can be improved by prebending these plates, creating a larger contact surface area and increasing compression at the osteotomy site. Nunamaker and Perren[11] wrote that prestressing the plate before fixation prevents the transverse-cut osteotomy junction from opening and increases stability. Therefore, we believe that, compared with the gold-standard of transverse-cut junctions fixed with prebent plates, concave-convex allograft junctions fixed with prebent plates can further improve contact surface area and stability.

Furthermore, an important factor in proper bone healing is pressure distribution. Cascio and colleagues[12] compared the mechanical advantages of sigmoid osteotomy over transverse-cut and step-cut osteotomies. They wrote that, compared with other osteotomies, sigmoid osteotomies allow for a more uniform pressure distribution and enlarge the contact surface area. Describing pressure distribution as transmission of the load applied to a fragment through the osteotomy gap to an opposing bone fragment, they indicated it can be thought of as quality of contact, as opposed to quantity of contact with respect to contact area. Uniform distribution of pressure is important in allowing a proportionate load on the full surface of the osteotomy junction. Disproportionate pressure increases stress on the bone, which in turn leads to increased allograft junction failure.[12]

Other osteotomy techniques (eg, transverse- or step-cut osteotomies) have been found to enlarge contact surface area and increase stability but can be difficult and time-consuming intraoperatively, as they require perfectly parallel or right-angle cuts to ensure proper bone apposition and compression to avoid nonunion or malunion. Compared with other techniques, our approach to allograft junctions allows for simpler intraoperative junction-site preparation, which may help reduce the time needed for allograft junction preparation.

In the present study, acetabular and femoral head reamers, commonly used in hip resurfacing procedures, were used to create concave-convex allograft junctions in polyresin sawbone models. The contact surface area and the percent contact surface area of these junctions were compared with those of matched and nonmatched transverse-cut allograft junctions. To our knowledge, this study is the first to evaluate concave-convex allograft junctions fixed with prebent or flat locking plates used for oncologic allograft reconstruction.

Analysis showed a statistically significantly higher mean percent contact surface area with the concave-convex configuration than with the other configurations using the same fixation method. Compared with the straight transverse cuts observed in this study, the circular junctions created by reamers naturally enlarge the potential contact surface area of concave-convex junctions. Mean surface contact area was more than doubled with concave-convex junctions compared with transverse-cut osteotomies.

In accordance with previous studies, a statistically significant increase in percent contact surface area was found between the matched transverse-cut configuration fixed with prebent plate and the matched transverse-cut configuration fixed with flat plate. Comparisons of the gold standard of transverse-cut osteotomies fixed with prebent plates and concave-convex allograft junctions fixed with prebent plates showed that concave-convex configurations fixed with prebent plates had a statistically significant increase in percent contact surface area, and concave-convex configurations fixed with flat plates did not (Figure 9). These factors led us to believe that use of concave-convex junctions, particularly those fixed with prebent plates, can promote better healing at the allograft junction because of the larger contact surface area.

Pressure distribution was also examined to locate any uneven distribution of pressure at those allograft junctions. Uneven distribution may create stress factors, which in turn can contribute to potential junction failure. Analysis of the Pressurex film revealed a more uniform distribution of contact across the entire junction site with concave-convex allograft junctions, as opposed to areas of focal concentration in the other groups. Although this observation is subjective, it was uniformly consistent. The increased uniformity in pressure distribution demonstrated by concave-convex allograft junctions will likely assist in decreasing the stress caused by this type of uneven pressure distribution.

Although the concave-convex configuration must initially be cut transversely, as is the case with the other configurations, perfect cuts are not necessary. The concave-convex reaming device configures the ends into a ball-and-socket configuration, facilitating manipulation and apposition of the 2 opposing ends. This allograft junction configuration may simplify intraoperative creation of allograft junctions.

The limitations of our study need to be considered before extrapolating the results for clinical application. We were not able to assess other factors contributing to nonunion, such as infection and chemotherapy, in our model. Our model was not compared with step-cut osteotomy junctions. However, as the transverse-cut osteotomy remains the clinical gold standard, our chief objective was to compare that standard—prebent plates with transverse-cut osteotomies—with our proposed method. Undoubtedly, a biomechanical study assessing the stability of these junctions, in addition to an in vivo animal study assessing the healing properties of these novel junctions compared with transverse- and step-cut configurations, would be necessary to fully assess the mechanical and physical properties at these sites.

Enlarging the host–allograft contact surface area and increasing the uniformity of pressure distribution across the construct may improve healing and minimize allograft–host nonunions. If this concave–convex allograft junction proves to be effective in increasing bone healing and decreasing time to healing, it will revolutionize daily orthopedic procedures by facilitating intraoperative junction-site preparation.

AUTHORS' DISCLOSURE STATEMENT

The authors report no actual or potential conflict of interest in relation to this article.

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