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DOI: 10.1177/19476035241308535
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Risk of Chondral Fracture During Implantation of Distal Femur Osteochondral Autograft Plugs: A Human Cadaveric Comparison of Four Different Donor Regions

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Abstract

Introduction. Distal femoral cartilage lesions can be treated using osteochondral autograft transfer (OAT). When impacting plugs into a recipient site, the cartilage may fracture. This study aimed to analyze OAT donor regions and impaction energies to identify characteristics that lead to fracture. *Methods.* Fifteen cadaver femurs were used with OAT plugs harvested from the following regions: lateral and medial trochlea (LT and MT), lateral and medial intercondylar notch (LIN and MIN). Plugs were impacted into a bone surrogate block using a custom anvil-type system with pre-determined impact heights; 30, 50, 70, and 90 mm. Each plug's cartilage was examined and determined to be intact or fractured. Chi-square was used to compare the rate of chondral fracture for each region. *Results.* In all, 221 plugs were included. The overall rate of chondral fracture was 45.7%. There was a significant difference in the rate of fracture between regions, with LIN, MIN, LT, and MT, having a fracture rate of 46.6%, 62.7%, 25.0%, and 51.9%, respectively ($P = 0.001$). An impact height of 30 mm resulted in a fracture rate of 17.7%. Increasing the impact height from 30 to 50 mm resulted in significantly increased chondral fracture risk ($P = 0.001$). *Conclusion.* Different donor regions have varying rates of chondral fracture during OAT plug impaction, with the lateral and medial trochlea being the most resistant to chondral fracture at lower forces. Increased impact energy increases risk of chondral fracture. Surgeons should maintain caution and utilize lower impact energy when inserting OAT plugs.

Keywords
osteochondral defect, cartilage, knee, autograft

Introduction

Cartilage lesions arise due to various etiologies including high-energy impacts, repetitive low-energy impacts, twisting of a joint while weight-bearing, and gradual wear-and-tear.[1,2] Such injuries are often found in the young, healthy, athletic population with reports of focal cartilage defects in up to 36% of all athletes, and asymptomatic lesions in 59% of basketball players.[1,3,4] Without treatment these defects may lead to significant pain, morbidity, and early onset osteoarthritis.[4-8] Several treatment options for chondral defects have been described in the current literature with varying rates of survivorship, including microfracture, subchondral drilling, matrix-assisted chondrocyte implantation (MACI), and osteochondral allograft transplant (OCA).[6,7,9-12]

Traditionally, microfracture is used for defects less than 2–4 cm^2, though this technique has poor outcomes beyond 5 years.[10] Subchondral drilling, an alternative to microfracture, carries the risk of thermal burn to regional chondrocytes.[12] The MACI procedure is used for large

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lesions and has reported success rates of 78% at 5 years and 51% beyond 10 years.[13,14] Another treatment option for larger defects is OCA, which has demonstrated survivorship of 82% at ten years. The allograft tissue used is a relatively inert biological substance that is ideally donor-recipient matched by ABO blood group but does not require extensive compatibility testing or anti-immunologic therapy.[15,16] Alternatively, treatment of chondral defects using osteochondral autograft transplantation (OAT) has reported survival rates of 89.5% at five years and 88.1% at ten years.[17] It has also been shown to offer athletes the quickest return to play compared with other treatment options for articular lesions.[18]

The OAT technique involves removing a healthy osteochondral plug from a limited weight-bearing portion of the distal femur and implanting it into the chondral defect. It is typically used for lesions that are 2 cm or less in diameter. After implantation, the donor site is then backfilled with an osteochondral allograft. A critical portion of the procedure is impacting the graft into the defect until it sits flush with the surrounding cartilage. During the impaction process fractures may occur in the graft, either in the cartilage or in the underlying bone.[19] Several donor sites have been described for harvest, including the lateral intercondylar notch (LIN), medial intercondylar notch (MIN), lateral trochlea (LT), and medial trochlea (MT). However, no literature has been published comparing the risk of chondral fracture during implantation among these common donor sites. Such data would allow for selection of ideal grafts from regions less prone to damage during impaction. The primary aim of this study is to examine the risk of graft fracture during impaction from each of the main donor sites: LIN, MIN, LT, and MT. The secondary aim of this study is to investigate the optimal impaction energy that minimizes the risk of OAT graft fracture. It was hypothesized that grafts from lateral donor sites would be at a higher risk of chondral fracture during impaction.

Methods

This study was approved by our site's Institutional Review Board (approval number: STUDY00001820, July 22, 2021). Fifteen cadaver knees were used in this study, comprised of eight right knees and seven left knees. Bilateral knees were used from six cadavers, and unilateral knees were used from three cadavers. The distal femur was systematically divided into four regions: LIN, MIN, LT, and MT. Each region was subdivided into four equal zones according to anatomic position within the region: far superior (FS), superior (S), inferior (I), and far inferior (FI). The average age of the cadaver knees was 77.8 years.

A custom apparatus (**Fig. 1**) was built to drop a 340 g head from preset heights to simulate impacting the graft into a recipient site. Attached to the head was a post that served as the impacting tool. The impact surface was a flat circle 6 mm in diameter. We established 30, 50, 70, and 90 mm as the standardized drop heights. The equation $PE = mgh$ with $g = 9.8$ m/s^2 was used to calculate the energy delivered at impact from each height, to ensure the apparatus delivered practical blows to the OAT plugs. The calculated energy for 30, 50, 70, and 90 mm was 0.100, 0.167, 0.233, or 0.300 J, respectively. Friction and air resistance were considered negligible and thus were not included in the impact energy calculations. Each plug was impacted only once. Bone surrogate blocks with a density of 20 pounds per cubic foot (PCF) (Sawbones USA, Vashon Island, WA) were used as the recipient site for the OAT plugs in the test apparatus. Bone blocks were prepared with a recipient site that was 6 mm in diameter and 10 mm deep that grafts would be impacted into. Grafts were harvested using an OATS kit (Arthrex, Naples, FL) set to 6 mm diameter and 12 mm depth. Care was taken to ensure the grafts were harvested perpendicular to the surface of the harvest site. In each region (LT, MT, LIN, & MIN) of each cadaveric knee, four plugs from specific zones (S, FS, I, & FI) were extracted (**Fig. 2**). Additional plugs were extracted from areas just outside the specified testing zones, these were considered quality control plugs. All plugs were

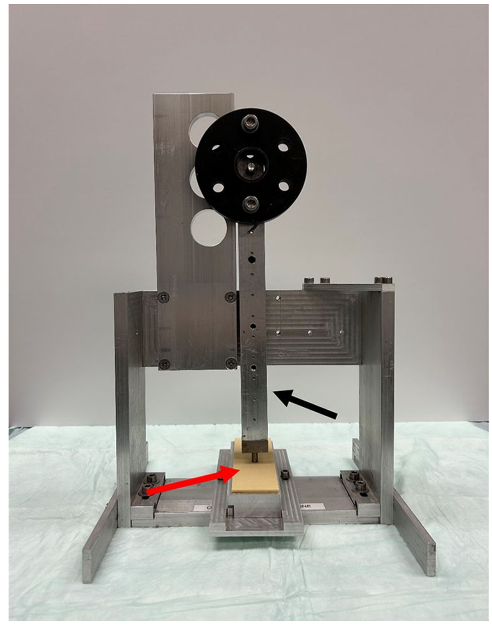

Figure 1. The custom testing apparatus used to deliver pre-calculated impaction energies to the osteochondral autograft transfer (OAT) plugs. A 340 g head (black arrow) was dropped from preset heights onto an OAT plug that was placed in a bone surrogate block (red arrow).

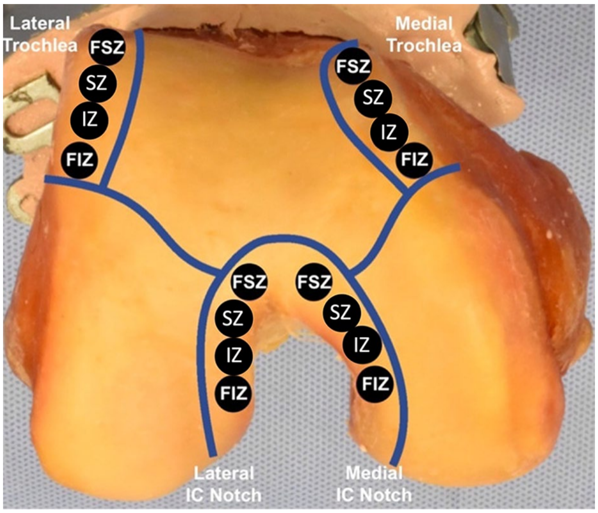

Figure 2. View of the articular surface of a right distal femur with regions and specific locations of osteochondral autograft transfer plug harvest marked (black circles). The harvest regions are demarcated with blue lines. FSZ = far superior zone; SZ = superior zone; IZ = inferior zone; FIZ = far inferior zone; IC = intercondylar.

removed from the harvesting tool and examined for structural defects that may have occurred during the extraction process; damaged plugs were removed from the study sample. Plugs were not placed back into the harvesting tool or sleeve prior to impaction by the test apparatus. Each knee was randomized to a drop height, and all OAT plugs from a given knee were impacted from the same height. Following a single impaction event, each OAT plug was grossly examined for chondral injury and was classified as either fractured or intact. A chondral fracture was defined as a grossly visible crack in the chondral surface of the graft. Grafts were examined for chondral injury prior to extraction from the surrogate bone block.

Statistical Analysis

An *a priori* power analysis was completed to determine the number of plugs needed in each of the 4 groups to yield a power of 0.8. It was determined that 46 samples from each region were needed to achieve sufficient power. Age and sex descriptive statistics were collected on all cadaver specimens. We performed univariate statistical analysis using Chi-squared for categorical variables and an unpaired *t* test for continuous variables. This study used an alpha level of 0.05. Post hoc power analysis yielded a result of 0.849 following the removal of samples damaged during the extraction process.

Results

Three hundred plugs were harvested in total, 240 from the typical donor regions and 60 control plugs. After a thorough visual evaluation, 19 donor region plugs (7.9%) and 6 control plugs (10%) were excluded due to being damaged during extraction, leaving 221 donor region plugs and 54 control plugs. The excluded plugs included 8 (13%) from the MT region, 2 (3%) from the LIN region, and 9 (15%) from the MIN region.

The average cadaver age was 77.8 years (range 63-89 years). Five cadavers were males and four were females. There was no difference in the age among the different donor regions ($P = 0.869$) or among the different drop heights tested ($P = 0.243$) (**Table 1**). A regression analysis showed there was not a significant association between age and fracture rate of the plug ($P = 0.062$).

In total, 101 (45.7%) of the donor region plugs experienced a chondral fractured and 120 (54.3%) did not (**Fig. 3**). Of the quality control plugs, 3 (5.6%) experienced chondral fracture, and 51 (94.4%) did not. The LT region had the overall lowest rate of fracture at all tested heights during impaction (25%), while the MIN had the highest fracture rate (62.7%) (**Table 2** and **Fig. 4**). There was a

Table 1. Age of Cadaver Knees by OAT Donor Region and Impact Height.

	Variable	Mean Age	Std. Error	95 % CI	*p*-Value
Donor Region	LIN	75.6	1.085	73.5 – 77.8	0.869
	LT	75.8	1.066	73.7 – 77.9	
	MIN	76.6	1.157	74.3 – 78.8	
	MT	75.2	1.146	73.0 – 77.5	
Anvil Drop Height	30 mm	77.2	1.041	75.1 – 79.2	0.243
	50 mm	75.5	1.195	73.2 – 77.9	
	70 mm	74.0	1.183	71.7 – 76.3	
	90 mm	76.0	1.024	74.0 – 78.0	

The average age of cadavers used for osteochondral autograft transfer (OAT) plug harvest. Ages are provided by OAT harvest region and anvil drop height following removal of damaged grafts from the test sample. No significant difference in age is present in either group.
CI = confidence interval; LIN = lateral intercondylar notch; LT = lateral trochlea; MIN = medial intercondylar notch; MT = medial trochlea.

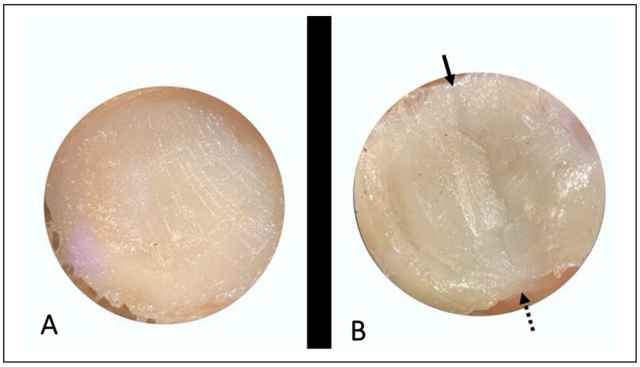

Figure 3. Close-up images of osteochondral autograft transfer (OAT) plugs following impaction into a simulated donor site. A) Focused image of an intact OAT donor graft. B) Focused image of an OAT donor graft with a chondral fracture after impact. The black arrows indicate each end of the fracture line. Images were taken through an arthroscope to simulate an intraoperative view of OAT plugs for demonstration purposes.

significant difference in fracture rate between donor sites ($P < 0.001$).

The lowest impaction height, 30 mm, fractured 11 of 62 samples (17.7%) of all donor regions. The rate of chondral fracture increased markedly at between the 30 and 50 mm drop height, with 53.2% fracturing at 50 mm. The chondral fracture rate was 56.3% at 70 mm and 59.4% at 90 mm (**Table 2** and **Fig. 5**). The chondral fracture rate at the 30 mm drop height for LT, LIN, MT, and MIN was 5%, 22.2%, 8.3%, and 41.7%, respectively. There was a difference in the OAT chondral fracture rate among the four different drop heights ($P < 0.001$).

Subgroup analysis demonstrated no difference in fracture rate between the 4 different drop heights for the LIN, LT, and MIN regions, though fracture rates were different between drop heights in the MT region (**Table 3**). The difference between fracture rates of the LIN, MIN, LT, and MT regions at the lowest impaction height was statistically significant ($P = 0.048$) (**Table 4**), with the LT and MT regions having the lowest chondral fracture rate. An impact height of 50 mm had an increased risk of fracture compared with 30 mm ($P < 0.001$). However, when increasing impaction height from 50 to 70 mm and from 70 to 90 mm, there was no significantly increased risk of fracture ($P = 0.838$ and $P = 0.847$, respectively).

Discussion

Osteochondral autograft transfer is a useful technique for improving both pain and functionality in patients with osteochondral lesions.[6,10,12] However, a major challenge is the potential for fracture of the autograft plug during impaction. This study tested 221 plugs from four separate donor regions of non-load-bearing cartilage: the LT, LIN, MT, and MIN. The two regions with the lowest fracture rate were the LT region (25%) and the LIN region (46.6%). It is unclear why these regions have lower risk of chondral fracture when compared with the MT and MIN regions. In addition, according to our data, impact energy plays a key role in the rate of chondral fracture regardless of which region of the distal femur they are harvested from. Our data demonstrate that an impaction energy greater than 0.100 J, equivalent to our 30 mm drop height, increases the rate of plug fracture (**Table 2**).

In addition to the chondral fracture pattern examined in this study, impaction of the autograft plug during the OAT procedure can lead to a "die-punch" fracture. "Die-punch" fractures are a form of intra-articular fracture where the articular cartilage and subchondral bone is impacted into cancellous bone. In a study performed by Borrelli *et al*., it was determined that irreversible cartilage damage may occur at the time of impact.[20] This further illustrates the point that minimizing the impact energy through the chondral portion of the graft is important for optimizing graft

Table 2. OAT Plug Chondral Fracture Rate by Donor Region and Impact Height.

	Variable (*n*)	Fractured	Intact	Fracture Rate (%)	95% Confidence Interval	*P*-value
Region	LT (60)	15	45	25%	15.8 – 37.2	<**0.001**
	LIN (58)	27	31	46.6%	34.3 – 59.2	
	MT (52)	27	25	51.9%	38.7 – 64.9	
	MIN (51)	32	19	62.7%	49.0 – 74.7	
Impact Height	30 mm (62)	11	51	17.7%	10.2 – 29.0	<**0.001**
	50 mm (47)	25	22	53.2%	39.2 – 66.7	
	70 mm (48)	27	21	56.3%	21.2 – 70.2	
	90 mm (64)	38	26	59.4%	47.2 – 71.3	

The overall chondral fracture rate of osteochondral autograft transfer plugs by donor region and by impact height. Plugs are grouped by harvest region and by anvil drop height. A significant difference was found in the fracture rate in both groupings.
LIN = lateral intercondylar notch; LT = lateral trochlea; MIN = medial intercondylar notch; MT = medial trochlea. OAT = osteochondral autograft transfer.
Bold values are statistically significant at α=0.05.

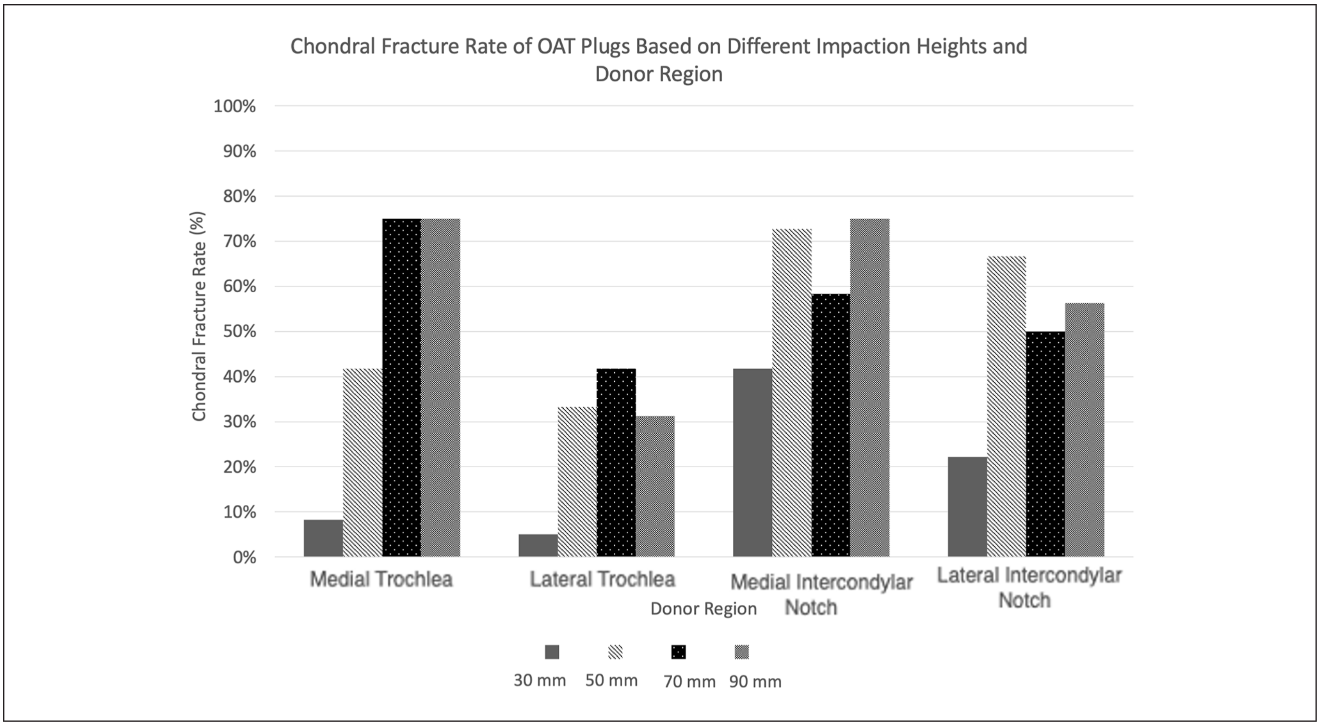

Figure 4. The chondral fracture rate of osteochondral autograft transfer plugs by donor region at all impaction heights tested (30, 50, 70, and 90 mm). A significant difference in fracture rate was found between donor sites. ($P < 0.001$).

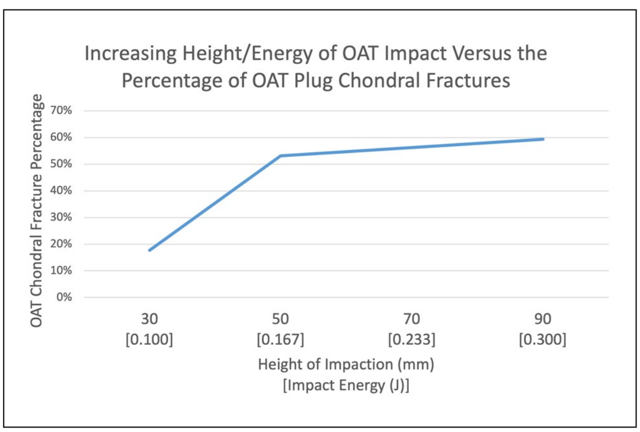

Figure 5. Overall rate of fracture from all harvest regions for each impact height, 30, 50, 70, and 90 mm, resulting in fracture rates of 17.7%, 53.2%, 56.3%, and 59.4%, respectively. Plugs were impacted with a 340 g head into a bone surrogate block in a custom testing apparatus. A significant difference in fracture rate was found between impact heights. ($P < 0.001$).

viability in the postoperative period. To further decrease risk of fracture and optimize viability, impacts during graft insertion should remain below 400 N (<10 MPa). This force should be applied as several low-force impacts, which have shown to be less damaging compared with fewer high-force impacts.[19]

The optimal OAT graft sits flush in the recipient site, with various techniques recommending the harvesting of plugs 1 to 2 mm longer than the recipient site.[21,22] Osteochondral plugs that sit proud or sink beneath the articular surface effectively act as osteochondral defects due to increased regional contact pressure. In a study on compressibility of OAT grafts by Massey *et al*., there was a significant difference in compressibility of the autografts based on their harvested region, with grafts harvested from the MT having the highest compressibility with a mean of 3.1 mm across all four donor zones.[21] Grafts with decreased compressibility can lead to a proud or sunk graft. One study demonstrated that osteochondral grafts 2 mm longer than the recipient site require increased force to seat properly.[23] This increased impaction energy elevates the risk for fracture of the graft and decreases chondrocyte viability within the graft.[23,24] Increased cartilage thickness may also provide protection against graft fracture during impaction. A previous study by Tasatan *et al*. examined cartilage thickness of OAT plugs from four regions of the distal femur, reporting the thickest cartilage among samples from the lateral trochlea.[25] This finding may explain the lower rate of chondral fracture seen in our study among samples from the LT region. Furthermore, the lowest cartilage thickness was found in the MIN region, where our study found the highest chondral fracture rate. Notably, a large mismatch between donor and recipient site cartilage thickness has been shown

Table 3. OAT Chondral Fracture Rates of Each Drop Height Within Each Donor Region.

Donor Region	Drop Height (mm)*	Fractured	Total	Fracture Rate	*P*-value
Lateral Trochlea	30	1	20	5%	0.078
	50	4	12	33%	
	70	5	12	42%	
	90	5	16	31%	
Lateral Intercondylar Notch	30	4	18	22%	0.075
	50	8	12	66%	
	70	6	12	50%	
	90	9	16	56%	
Medial Trochlea	30	1	12	8%	**0.001**
	50	5	12	42%	
	70	9	12	75%	
	90	12	16	75%	
Medial Intercondylar Notch	30	5	12	42%	0.275
	50	8	11	73%	
	70	7	12	58%	
	90	12	16	75%	

Subgroup analysis of fracture rates for each donor zone from the four drop heights. There is a significant difference in fracture rate between drop heights for the medial trochlea ($P = 0.001$), while other harvest sites had no difference in fracture rate.
*Drop height of 30, 50, 70, and 90mm are equal to 0.100, 0.167, 0.233, and 0.300 J.
OAT = Osteochondral Autograft Transfer.
Bold values are statistically significant at $\alpha = 0.05$.

Table 4. Chondral Fracture Rate of OAT Plugs Impacted From 30 mm.

Region (*n*)	Fractured	Intact	Fracture Rate (%)	*P*-value
Lateral Trochlea (20)	1	19	5%	**0.048**
Lateral Intercondylar Notch (18)	4	14	22.2%	
Medial Trochlea (12)	1	11	8.3%	
Medial Intercondylar Notch (12)	5	7	41.7%	

Fracture rate of osteochondral autograft transfer plugs that were impacted at the lowest impact height (30 mm) grouped by harvest region on the distal femur. A significant difference was found in the fracture rate between the regions ($P = 0.048$).
Bold values are statistically significant at $\alpha = 0.05$.

to create high-stress regions that may lead to graft failure.[26,27]

Although typical OAT recipients are younger than those included in this study,[22] we considered it appropriate to use specimens from older individuals as evidence suggests that certain biomechanical properties of young bone and older bone are not dissimilar.[28,29] One study examined biomechanical properties of the proximal tibia based on age.[28] The authors found that for trabecular bone, the modulus of elasticity for bone aged 13-39 years was 654 (304 MPa) while the modulus in bone aged 60-83 years was 613 (319 MPa). While these values are near one another in comparison with the middle-aged group's modulus (829 (422 MPa)), no statistical comparison was performed between the young and old groups. The modulus peaked toward the end of the fifth decade and then declined steadily.[28] Another study describes a poor correlation between mechanical properties and age in the distal femur.[30] These data were considered sufficient to provide support of using older specimens, despite OAT procedures usually occurring in younger patients.

However, a study published in 2018 examined the changes in the properties of articular cartilage, subchondral bone, and trabecular bone in the human knee joint from 12 cadaveric specimens aged 31-88.[29] The study suggests a strong correlation between increasing age and decreased cartilage shear storage modulus while also suggesting a moderate correlation with an increase in subchondral bone elastic modulus with increased age. Considering these findings, the advanced age of cadaveric specimens used in this study could have impacted the rate of fracture. Furthermore, the thickness of articular cartilage may have an impact on the chondral fracture rate. While this was not assessed in our study, doing so would strengthen future works in this area.

This study does have several limitations. First, this is an *in vitro* study on nonliving tissue, which may have different fracture characteristics than an *in vivo* OAT plug. Also, the use of a bone surrogate block for the graft recipient site may have altered graft chondral fracture rates compared with real bone. The fracture testing was performed in an apparatus that ensured consistent blows and energy transfer by the mallet. Given the likelihood of variability in mallet striking by human surgeons, hard or soft strikes may alter outcomes in the clinical setting. Nonetheless, this study may guide the practicing surgeon in which harvest sites are less likely to fracture during impaction. While estimated impact energy was calculated, the true contact pressure between graft and the testing apparatus was not measured. This may have been an influential factor in the rate of chondral fracture. In addition, we did not perform a histologic analysis. There may be undetectable cellular damage with certain impaction forces not reported in this study and this should be a focus of future research. Furthermore, our experimental design differs from the steps performed in a typical OAT surgery. Specifically, that the grafts were removed from the harvester in our experiment to facilitate examination prior to impaction. Finally, we did not record thickness of the cartilage in each of the grafts, which may have had an impact on chondral fracture rate.

Conclusion

There are different rates of chondral fracture among different donor regions during impaction of OAT plugs, with the lateral trochlea and medial trochlea being the most resistant to chondral fracture at lower forces. There is an increased risk of OAT chondral fracture with increased energy delivery by the mallet during impaction. Surgeons should use caution and utilize lower impact energy when inserting OAT plugs.

Acknowledgments and Funding

The authors acknowledge Baraa Shihadeh for preparation of manuscript. The author(s) received no financial support for the research, authorship, and/or publication of this article.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Approval

This project was approved by our Institutional Review Board, STUDY00001820.

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