Lateral Harvest of an Osseous-Based Quadriceps Tendon Autograft Results in Thinner Remaining Patellar Bone

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Background: Patellar fracture after quadriceps tendon (QT) autograft harvest for anterior cruciate ligament reconstruction (ACLR) has been reported in up to 8.8% of patients.

Purpose: To determine the thickness of the remaining patellar bone across the QT graft harvest location while providing clinical guidance for safely harvesting a patellar bone block when using a QT graft in ACLR.

Study Design: Descriptive laboratory study.

Methods: Medial and lateral QT graft boundaries were marked using a bone saw on 13 cadaveric patellae, and 3-dimensional computed tomography models were created. After the harvest of a virtual bone block with a maximum depth of 10 mm, the thickness of the remaining bone was measured across the graft harvest location in 9 zones. The thickness of the remaining bone was analyzed according to zone, graft harvest location, and patellar facet length. Risk zones were defined as <50% total patellar depth remaining.

Results: We observed substantial variability in QT bone block harvest location, in which the distance between the lateral boundary of the harvest location and the lateral patellar cortex was from 21.2% to 49.2% of the axial patellar width. There was significantly less bone remaining in the lateral columns (mean ± SD, 7.56 ± 2.19 mm) compared with the medial columns (9.83 ± 2.10 mm) of the graft harvest location ($P = .028$). The number of risk zones was significantly associated with distance to the lateral cortical edge, with an increase in 0.59 zones with every 1-mm decrease in distance to the lateral cortex edge ($b = -0.585$; $R^2 = 0.620$; $P = .001$). With every 1-mm increase in the distance of the lateral cortex to the lateral graft boundary, the thickness of bone remaining in the lateral column increased by 0.412 mm ($P < .001$). No risk zones were encountered when the lateral boundary of the harvest location was created 18.9 mm from the lateral edge of the patella or 43% of the total patellar width from the lateral edge.

Conclusion: Harvest of a more laterally based QT autograft bone block resulted in thinner remaining patellar thickness, increasing the potential of encountering a risk zone for fracture.

Clinical Relevance: Care should be taken to avoid harvesting the patellar bone block too laterally during ACLR.

Keywords: ACL reconstruction; patella; patellar fracture; quadriceps tendon

Anterior cruciate ligament (ACL) injuries are common, with a reported incidence of 68.6 per 100,000 person-years, and are successfully managed surgically with graft reconstruction.[10,20,23] In the young, active population, the bone–patellar tendon–bone (BPTB) autograft is commonly used, while the use of quadriceps tendon (QT) autografts has also been reported.[3,11] Previous studies have shown reliable and satisfactory results after reconstruction using QT autograft during ACL reconstruction (ACLR).[18,21] In addition, QT autografts have been reported to cause less anterior knee pain compared with BPTB autografts,[7,18] while providing equivalent clinical outcomes and biomechanical properties.[8,9,14,24] During QT harvest, a patellar bone block may or may not be included. In cases where the length of the QT is <6 cm, some have argued that the harvested tendon should include a patellar bone block.[31] Moreover, bone-to-bone healing within the ACL tunnels has been shown to be superior when compared with tendon-bone healing.[32] When patellar bone is harvested, there is a concern for subsequent patellar fracture, reported to occur in up to 8.8% of cases.[6,15]

The Orthopaedic Journal of Sports Medicine, 10(5), 23259671221093685
DOI: 10.1177/23259671221093685

The decision on where to harvest the patellar bone block is typically determined based on where the longest QT graft can be obtained. However, the longest portion of the QT may not always correspond with the central portion of the patella.[17] Lippe et al[17] demonstrated the proximal peak of the QT to be located 61.6% (range, 53.8% to 68.0%) from the medial border of the QT insertion. As such, optimal harvest of the QT during ACLR may necessitate removal of the patellar bone block lateral to the superior pole. In a quantitative analysis of patellar fractures after ACLR using QT autograft, Ferrer et al[5] found that bone blocks that were harvested relatively deeper and more laterally were more likely to result in patellar fracture. As such, a better understanding of QT harvest location with bony depth is necessary to minimize fracture risk during QT harvest.

The purpose of this study was to define the thickness of patellar bone remaining across the QT graft harvest location using cadaveric specimens while providing clinical guidance for safely harvesting a patellar bone block when utilizing a QT autograft during ACLR. We hypothesized that the remaining thickness of the patella would decrease in the proximal and lateral aspects of the graft harvest site.

METHODS

Specimen Preparation and Graft Marking

This study was exempt from institutional review board approval owing to the use of deidentified cadaveric specimens. A total of 13 nonpaired, fresh frozen cadaveric specimens were used for this study. Specimen number was chosen based on previous studies.[5,12,17,25] The cadaveric specimens used in this study were donated to a tissue bank for the purpose of medical research and then purchased by our institution. Specimens were excluded if there was any evidence of previous knee surgery or the presence of osteophytes on the proximal aspect of the patella.

Location of ideal QT-bone harvest site on the patella was determined via identification of the longest portion of the rectus femoris tendon by a board-certified orthopaedic surgeon(J.C.). The point on the proximal pole of the patella corresponding to the longest aspect of the rectus femoris tendon was marked using a marking pen. Graft boundaries were then marked 5 mm medial and lateral to the marked point using a ruler with markings to the 10th of a centimeter to create a 10-mm graft width. Graft boundaries were then scored to a depth of approximately 2 mm using a surgical oscillating saw. The length of the bone block was marked to be 20 mm, starting from the superior pole of the patella at the anterior face.

Measurement of Bone Thickness and Zone Creation

Computed tomography (CT; 16-row CT scanner [Brilliance 16-slice scanner; Philips]) images of the specimens were acquired by use of 0.625-mm continuous slices (120 kV, 100 mA, 1.0-second duration, 20-cm field of view, 512 × 512 matrices) at our institution. Three-dimensional (3-D) models of the patella were then created and exported into polygon models using a 3-D reconstruction software program (Mimics; Materialise Inc). The following procedures and analyses were performed using custom-written programs coded in Microsoft Visual C++ with Microsoft Foundation Class programming environment (Microsoft Corp).

A graft anterior surface of each patella was segmented inside the marked graft boundaries, and a point-cloud model of the anterior surface including approximately 1000 data points was created. The most medial, lateral, and caudal (nose) points of each patella were determined using temporal local coordinates of each patella calculated via eigenvectors of the patellar model. A plane including these 3 points was created, and a normal vector of the plane was calculated. A patellar coordinate was then determined by transforming the temporal local coordinates so that the anteroposterior axis matched the normal vector of the plane (Figure 1). Vectors parallel to the normal vector originating from each point of the graft anterior surface model were calculated, and distances from the anterior points to the plane and from the plane to the intersection of the posterior surface were calculated. The plane was then moved parallel to the original plane so that the maximum anterior distance became 10.0 mm, simulating a 10.0 mm—thick bone block harvest. The thickness of bone remaining posterior to the plane (posterior distance) was used in analysis.

Four corner points of the anterior graft surface model were detected, and 9 zones, or regions of interest (ROIs), were determined via tripartition of each side (Figure 2). The posterior zones were determined via intersections of the normal vectors described earlier (projection of the anterior zones on the posterior surface) (Figure 2).

Anatomic Measurements

All anatomic measurements were made using CT images after graft boundary marking (Figure 3). The total axial

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Final revision submitted February 6, 2022; accepted February 23, 2022.

One or more of the authors has declared the following potential conflict of interest or source of funding: D.M.K. has received grant support from Arthrex and education payments from Medwest and Smith & Nephew. A.B.Y. has received education payments from Arthrex/Medwest, consulting fees from JRF Ortho and Olympus American, and honoraria from JRF Ortho. J.C. has received education payments from Arthrex and Smith & Nephew; consulting fees from DePuy, Linvatec, Smith & Nephew, and Arthrex; speaking fees from Linvatec; and hospitality payments from Stryker. AOSSM checks author disclosures against the Open Payments Database (OPD). AOSSM has not conducted an independent investigation on the OPD and disclaims any liability or responsibility relating thereto.

Ethical approval was not sought for the present study.

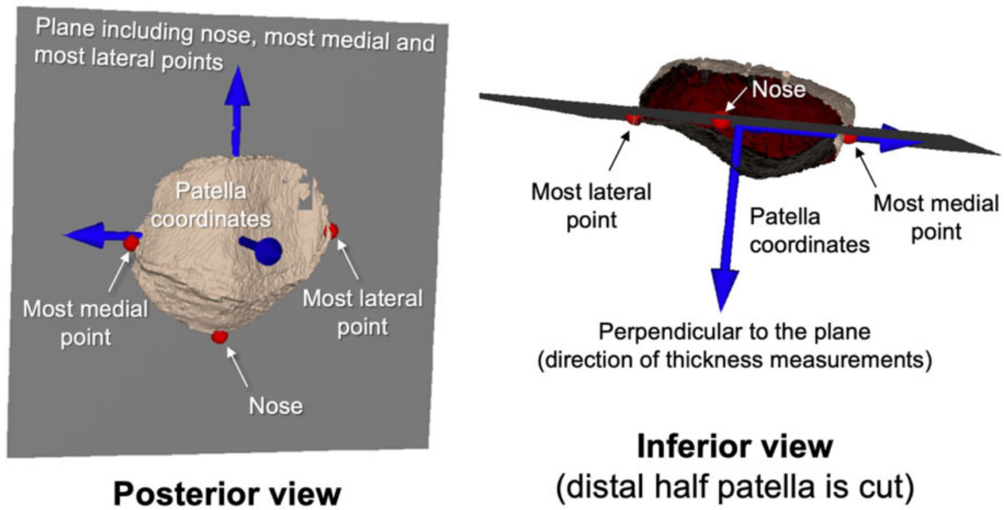

Figure 1. Defined coronal plane through the nose, most medial, and most lateral points of each patella from the posterior and inferior views of a right patella.

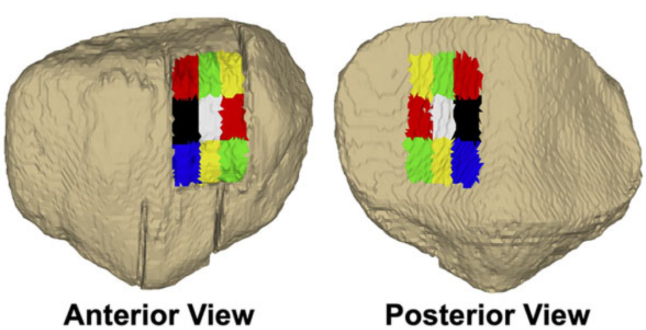

Figure 2. Representation of the 9 regions of interest used in analysis from the anterior and posterior views of a left patella.

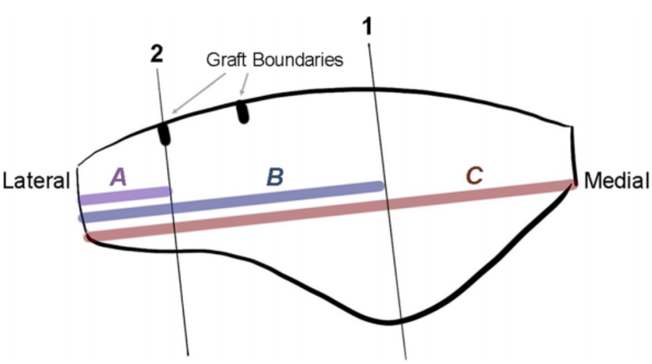

Figure 3. Anatomic measurements performed on computed tomography scan after graft boundary marking. Line 1 bisects the patellar ridge, and line 2 demarcates the most lateral graft boundary. Both lines are drawn perpendicular to the widest axial width of the patella, line *C*. Line *B* represents the measured distance from the lateral cortex to line 1, and line *A* is the measured distance from the lateral cortex to line 2. Percentage of lateral facet to axial width = *B*/*C*; percentage of graft harvest distance to axial width = *A*/*C*.

width of the patella was measured from the widest measurement of the osseus plane (line *C*). Two perpendicular lines were then drawn: the first to bisect the patellar ridge, differentiating the lateral and medial facets (line 1), and the second from the lateral graft harvest boundary (line 2). The length of the lateral facet was measured from the most lateral cortex edge to line 1 (line *B*), and the graft harvest distance to the lateral edge of the patella was measured from the most lateral cortex edge to line 2 (line *A*). The lateral facet and graft harvest distance measurements were also converted to equivalent percentage measurements over the total axial width (*B*/*C* and *A*/*C*, respectively) to account for variation in patellar size. Tibial width was measured at the greatest diameter in the axial plane.

In addition to measuring the thickness of bone remaining after harvest in millimeters, we quantified the remaining percentage of the total patellar width within each zone. Based on previous literature, zones that had $<50\%$ of bone remaining after virtual harvest were defined as "risk" zones for fracture.[6] The incidence of at least 1 risk zone in each specimen and the average number of zones of risk were quantified. Anatomic factors associated with increased number of risk zones were analyzed using linear regression.

Statistical Analysis

The data were determined to be parametric using the Shapiro-Wilk test. Descriptive analysis was performed using the Student t test for comparison of the thickness of remaining bone in the medial and lateral columns and for comparison of specimens with or without at least 1 risk zone with regard to the distance between the lateral graft boundary and lateral patellar edge, tibial width, osseous width, and lateral facet length. A 1-way analysis of variance was used to compare the thickness of bone remaining in each ROI, and post hoc pairwise Tukey tests were used

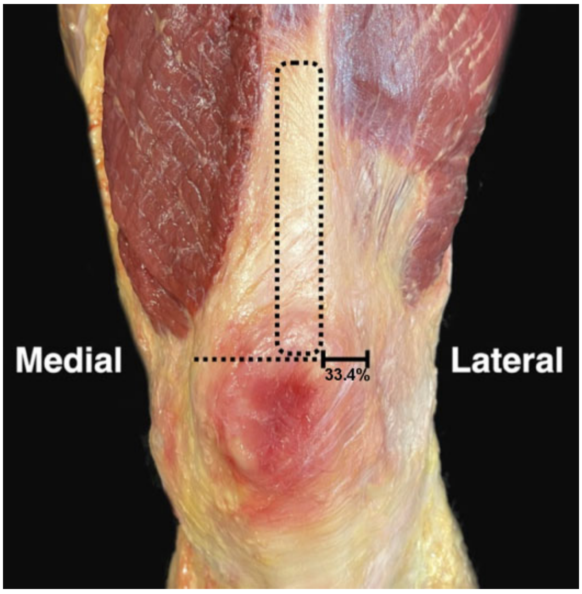

Figure 4. Quadriceps tendon insertion on the patella demonstrating that the average distance between the lateral patellar cortex edge and the lateral border of the bone block harvest location (dotted outline) was 33.4% of the total axial width of the patella.

where appropriate, with results presented as mean ± standard deviation. Linear regression analysis was performed to assess predictive risk factors for bone thickness. Due to collinearity ($R^2 > 0.90$) of the anatomic measurements and equivalent percentage measurements, each equivalent measurement was included in a separate multivariate model where appropriate. Statistical significance was defined as $P < .05$. All statistical analyses were performed using STATA 16.1 (STATACorp).

RESULTS

Anatomic Measurements

The mean axial width (line *C*) of the 13 patellae was 41.5 ± 4.3 mm, with the lateral facet (line *B*) measuring an average of 23.9 ± 3.1 mm. The mean distance from the lateral graft boundary to the lateral patellar cortex (line *A*) was 13.9 ± 4.6 mm. When converted to equivalent percentage measurements, the lateral facet was 57.7% ± 5.2% (range, 46.4%-67.3%) of the total axial width, and the lateral border of the graft harvest location was 33.4% ± 9.7% (range, 21.2%-49.2%) of the total axial width from the lateral cortex edge (Figure 4). The mean tibial width was 74.3 ± 4.5 mm (range, 66.3-80.4 mm).

Significantly greater bone remained along the medial aspect of the harvest zone when compared with the lateral column (9.8 ± 2.1 vs 7.6 ± 2.2 mm; $P = .028$) (Table 1). Overall, 77% (n = 10/13) of patellae had at least 1 zone with <50% total width remaining, while the average number of risk zones per specimen was 4.3 ± 3.4 (range, 0-9). Risk zones were present most frequently at the proximal lateral (9/13) and central lateral (9/13) zones (Figure 5).

TABLE 1
Mean Thickness and Percentage of Bone Remaining in Each Zone After Virtual Bone Block Harvest[a]

	Medial	Central	Lateral
Proximal	9.6 ± 2.0 mm	8.5 ± 2.2 mm	7.1 ± 2.2 mm
	53.8% ± 7.6%	49.9% ± 8.3%	45.4% ± 9.0%
Central	9.9 ± 1.8 mm	8.8 ± 2.2 mm	7.4 ± 2.2 mm
	52.3% ± 6.3%	48.6% ± 7.3%	44.2% ± 8.3%
Distal	10.5 ± 2.0 mm	9.5 ± 2.5 mm	8.2 ± 2.5 mm
	54.9% ± 6.7%	52.1% ± 8.3%	48.7% ± 9.5%

[a]Data are reported as mean ± SD.

Anatomic Factors Related to Bone Remaining After Virtual Graft Harvest

Univariate regression analysis showed that the thickness of the lateral column was significantly associated with total osseus width of the patella ($b = 0.298$; $R^2 = 0.347$; $P = .034$) as well as tibial width ($b = 0.311$; $R^2 = 0.404$; $P = .020$). The length of the lateral facet was also significantly associated with thickness of the lateral column, with a 0.527-mm increase in bone remaining with every 1-mm increase in the length of the lateral facet ($b = 0.527$; $R^2 = 0.554$; $P = .004$). In addition, with every 1-mm increase in distance of graft harvest from the lateral edge, the thickness of bone remaining in the lateral column increased by 0.412 mm ($b = 0.412$; $R^2 = 0.741$; $P < .001$) (Figure 6). A similar effect was observed when utilizing percentage harvest location of total axial width ($b = 0.172$; $R^2 = 0.587$; $P = .002$). The percentage lateral facet of total axial width was not significantly correlated with the thickness of the lateral column, central column, or medial column ($P = .186$, .276, and .172, respectively).

In a multivariate model, only millimeter distance of graft harvest remained significantly predictive of bone remaining in the lateral column ($b = 0.342$, $R^2 = 0.815$; $P = .011$). When taken as a percentage measurement, the graft location remained the only significant predictor with slightly improved overall model fit ($b = 0.142$; $R^2 = 0.818$; $P = .010$).

Patellae with at least 1 risk zone had an ideal lateral graft border that was 30.5% ± 9.0% of the total width from the lateral cortex edge, which was significantly closer to the cortex compared with patellae without risk zones (43.0% ± 5.3%; $P = .045$). When these measurements were converted to millimeters, the patellae with at least 1 risk zone had graft harvest sites 12.5 ± 3.6 mm from the lateral cortex, whereas patellae without risk zones had graft harvest sites 18.9 ± 4.4 mm from the cortex ($P = .024$). There were no significant differences in tibial width, osseus width, lateral facet length, or percentage lateral facet between patellae with or without at least 1 risk zone. The number of risk zones demonstrated a significant association with distance to the lateral cortex edge, with an increase in 0.59 zones with every millimeter decrease to the lateral cortex ($b =$ -

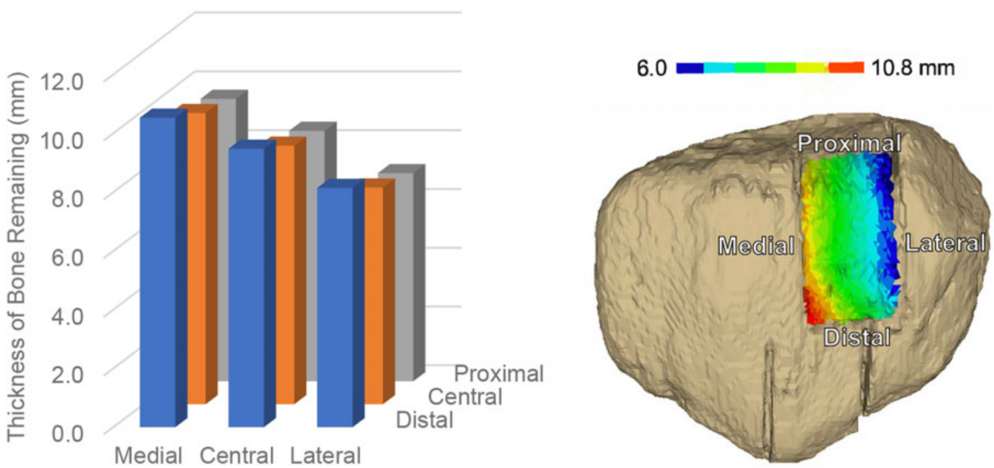

Figure 5. Measurement of bone thickness remaining in each zone after virtual patellar bone block harvest. Results indicated significantly thinner bone at the lateral aspect of the patella relative to the medial patella. Schematic representation of bone remaining in each zone after harvest. Increasing red gradient indicates thinner bone.

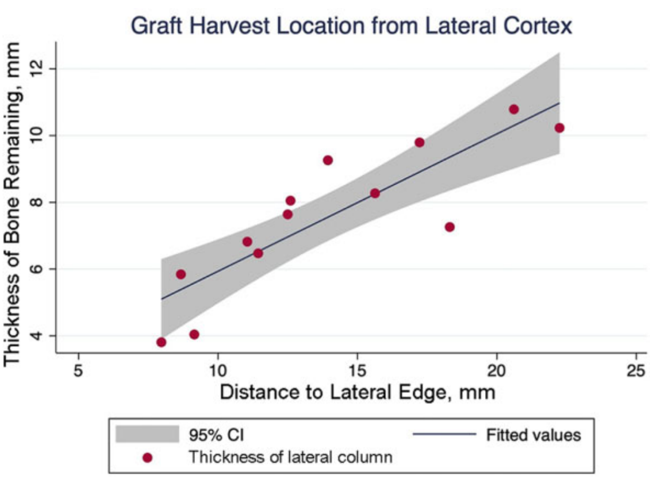

Figure 6. Graft eccentricity was significantly associated with thinner bone at the lateral column remaining after harvest.

0.585; R^2 = 0.620; P = .001). The equivalent percentage measurement for graft harvest location demonstrated a similar relationship, with an increase in 0.26 zones of risk with every 1% of width closer to the lateral cortex, although with lower overall model fit (b = -0.258; R^2 = 0.544; P = .004). Percentage lateral facet, tibial width, osseus width, and lateral facet length did not significantly predict number of risk zones (P > .05).

DISCUSSION

The important findings of this investigation were the presence of variability in patellar thickness based on the location of QT autograft harvest, with significantly less bone remaining in the lateral column of the graft harvest location compared with the medial column. The number of risk zones after graft harvest was significantly associated with the distance from the lateral cortex to the lateral graft boundary, with each millimeter increase in the distance of the lateral cortex to the lateral graft boundary leading to the thickness of bone remaining in the lateral column increasing by 0.412 mm.

Although previous studies have reported satisfactory clinical outcomes after ACLR using QT autografts, patellar bone block harvest has been associated with a risk of patellar fracture.[2,4,7,13,16,20,27-29] The risk of patellar fracture after ACLR using BPTB grafts has been reported to range from 0.3% to 1.8%, while higher rates have been reported after QT autograft harvest.[4,22,30] In their case series examining outcomes after ACLR using QT autograft in 57 patients, Fu et al[6] reported that 8.8% of patients sustained a patellar fracture within 2-year follow-up. Of note, 2 out of 5 of the identified fractures were detected on postoperative advanced imaging and were not clinically significant. The authors identified possible risk factors for fracture to include eccentric harvest site (medial or lateral), harvest >50% of the anteroposterior thickness, harvest >50% of the mediolateral width of the patella, failure of the bone graft to incorporate, and presence of a stress riser at the corner of the graft harvest site.[6] When using 3-D reconstructions of patellae included in the investigation by Fu et al, Ferrer et al[5] performed a quantitative analysis to determine additional factors associated with patellar fracture. The authors reported that, in comparison with the patellae without fracture, those with fractures had grafts that were harvested more laterally.[5] Although the authors defined a different plane from that in our study for measuring patellar thickness, Ferrer et al reported that at the central point of graft harvest, fractured patellae had bone blocks with >15% depth of the patella when compared with nonfractured patellae. Moreover, the authors found that overall patellar thickness was not associated with a higher risk of fracture. Rather, the fracture risk was dependent on the percentage of bone harvested, comparable with that in the report by Fu et al of harvesting >50% of the patellar width being associated with fracture. Prevention of postoperative patellar fracture after ACLR is important, as this complication may necessitate fixation, leading to increased rehabilitation time and prolonging return-to-sports timing to allow for bony healing.[19]

While controlling for bone block width, our study aimed to define the thickness of the patella across the entire graft harvest location to determine a potential cause for patellar fractures when grafts were harvested eccentrically. As cited by Fu et al[6] and Ferrer et al[5] of laterally located grafts being associated with greater fracture risk, our results showed that the ROIs with the thickest mean remaining bone were located in the medial columns while the ROIs in the lateral columns demonstrated the thinnest mean remaining bone. When analyzing graft eccentricity and risk zone presence (defined as >50% of the anteroposterior thickness), we observed that risk zones were present most frequently in the proximal lateral and central lateral zones. On average, the percentage of bone remaining was >50% in all the medial ROIs and <50% in all lateral zones, suggesting that the more laterally a graft is harvested, the more likely a surgeon is to enter a risk zone. The number of risk zones was significantly associated with the distance from the lateral graft boundary to the lateral cortex, both in raw distance and in percentage of total axial width. Clinically, these results can be used to help determine the ideal position for QT autograft harvest: if feasible with the location of the QT, risks zones on the remaining patella may be avoided if the lateral border of the bone block is created at least 12.5 mm from the lateral edge of the patella or at least 43% of the total patellar axial width from the lateral edge.

When analyzing the relationship between the distance from the lateral edge of the graft boundary to the lateral cortex of the patella and the thickness of bone remaining in the lateral column, this study found smaller distances to be associated with thinner bone, which was expected given the medially based location of the central ridge of the patella. With each millimeter increase in the distance from the lateral cortex to the lateral graft boundary, the thickness of bone remaining in the lateral column increased by 0.412 mm, supporting harvest of a more medial graft to avoid further decreasing the thickness of laterally based bone. Interestingly, although there was a significant association between remaining bone in the lateral column and total osseous width of the patella or lateral facet length (representative of patient size), there were no significant differences between these measurements and the presence of at least 1 risk zone. These results support the findings of Ferrer et al,[5] who concluded that the percentage of total bone harvested was associated with fracture risk rather than the total thickness of the patella before bone block harvest. Clinically, this information may be used in preoperative planning, as the decision of whether to use a QT graft may be based on the location of the QT insertion on the patella instead of patellar thickness.

There remains a wide variety in where QT grafts are harvested on the patella. When considering the distance from the lateral graft boundary to the lateral patellar edge in percentage of total axial width of the patella, a wide range (21.2% to 49.2%) of graft harvest location was appreciated. While all graft boundaries were marked by a single board-certified orthopaedic surgeon according to the longest portion of the QT, there was a degree of variability due to anatomic factors. When considering where to harvest the patellar bone block, surgeons must take care in ensuring the resulting QT graft will be of adequate length and width. Yamasaki et al[31] reported that a tendon length of at least 60 mm was required for satisfactory ACLR using QT autograft, while other studies have reported that graft width measuring at least 7 to 8 mm decreases the risk for revision ACLR.[1,26] If feasible, the patellar bone block should be harvested more centrally or medially while obtaining appropriate QT length and width. If the planned QT graft harvest with bone block is noted to be too far lateral on the patella, surgeons may consider harvesting an all—soft tissue QT graft versus obtaining a bone plug of shorter depth (ie, 6 mm) followed by bone grafting. If adequate QT is present medially, a more medially based graft harvest may be performed. However, surgeons must be aware of the increased risk for a shorter soft tissue graft harvest proximally.

Limitations

This study is not without limitations. With the harvest of a virtual bone block, the thickest portion of the block was set to 10 mm, resulting in the remaining portions of the simulated bone block being <10 mm thick because of the natural curvature of the anterior face of the patella. While harvesting the graft during surgical procedures, some surgeons may make this measurement differently, resulting in different portions of the bone block that are ≥10 mm, which may affect the presence of risk zones across the graft location. Moreover, variations in the angulation of each cut may affect the remaining patellar thickness in the clinical setting. In addition, anatomic measurements were performed by only 1 investigator, resulting in the inability to perform inter- and intrarater reliability testing. Moreover, the length of the bone block was set to 20 mm, starting from the superior pole of the patella at the anterior face. This measurement may vary in clinical practice based on inherent anatomic difference in patellar morphology. The length of the tendon at the longest point was not measured in this study. As such, further research is required to determine clinical outcomes and patellar fracture incidence when harvesting a more medially based patellar bone block compared with a more laterally based bone block, while ensuring appropriate QT tendon and width. Furthermore, information on specimen characteristics, such as age, height, weight, and sex, was not available, which would have been useful in understanding the size of each patella. Although more laterally located graft harvest was shown to result in thinner remaining bone, we did not correlate this finding with the likelihood of patellar fracture via biomechanical testing. Future research is warranted to determine the association between fracture risk and the thickness of remaining bone across the bone block harvest location.

CONCLUSION

Harvest of a more laterally based QT autograft bone block during ACLR results in thinner remaining patellar thickness, increasing the potential of encountering a risk zone for fracture.

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