Original Article

Patellar Fracture Forces Are Not Affected by Proximal Versus Distal Bone Block Anterior Cruciate Ligament Reconstruction Harvest Sites in a Cadaveric Model

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Purpose: To quantify the maximum load to fracture in patellae from which bone—patellar tendon—bone (BPTB) and bone—quadriceps tendon (BQT) autografts have been harvested for anterior cruciate ligament reconstruction in a cadaveric model. **Methods:** Forty-six fresh-frozen patellae were isolated and divided into the BPTB harvest and BQT harvest groups with matching based on donor age and sex. Computed tomography scans were obtained to calculate bone mineral density (BMD) and patellar height, width, and thickness. BPTB and BQT grafts were harvested from the inferior patella and superior patella, respectively, and then ramped to failure in a 3-point bend test configuration to simulate a postoperative fracture produced by a direct impact after a fall. The presence of fracture, fracture pattern, and maximum load to fracture were recorded. Donor demographic characteristics; patellar height, width, and thickness; and maximum load were compared by the Student *t* test. Pearson correlations were used to determine whether maximum load was affected by BMD or patellar morphology. The level of significance was set at $P < .05$. **Results:** Maximum load to fracture was not significantly different ($P = .91$) between the BPTB (5.0 ± 2.3 kN) and BQT (5.1 ± 2.6 kN) groups. Maximum load to fracture in the BPTB group did not correlate with BMD ($P = .57$) or patellar measurements ($P = .57$ for thickness, $P = .43$ for width, and $P = .45$ for height). Maximum load to fracture in the BQT group positively correlated with BMD and negatively correlated with patellar height. Maximum load to fracture in the BQT group did not correlate with patellar thickness or width. Fracture through the harvest site was observed in 87% of BPTB specimens and 78% of BQT specimens. **Conclusions:** The location of the BPTB or BQT autograft harvest site did not significantly affect patellar load to fracture in a cadaveric model. **Clinical Relevance:** It is important to understand patellar morphology and the effect of BPTB and BQT graft harvest-site locations on the biomechanical strength of the patella after anterior cruciate ligament reconstruction.

Postoperative patellar fracture after bone—patellar tendon—bone (BPTB) autograft harvesting for anterior cruciate ligament (ACL) reconstruction is a devastating injury that substantially impacts postoperative rehabilitation and outcomes. The prevalence of postoperative patellar fracture in ACL reconstruction patients is approximately 0.5% to 2%.[1,2] Fracture typically occurs owing to direct trauma, such as a fall or contact collision such as in a motor vehicle accident. Indirect trauma related to overuse or overload during rehabilitation is also a possible causative factor for postoperative patellar fracture.

Quadriceps tendon (QT) autografts have been the subject of increasing interest and investigation in recent years. QT autografts may consist of all soft tissue or may incorporate a bone plug (bone—quadriceps-tendon [BQT]). The literature has shown that QT autografts are comparable to BPTB autografts in terms of knee stability, functional outcomes, and graft rupture rates.[3-10] BQT autografts have recently gained popularity as an alternative to BPTB grafts because of the larger graft thickness and higher load to failure.[11-13] Additionally, BQT autografts add length needed for ACL reconstruction compared with all-tendon QT autografts. The use of a

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bone plug in BQT grafts aids in bony healing and may be particularly useful in revision settings.[14] However, BQT grafts also carry the risk of postoperative patellar fracture. The fracture rate for BQT autografts has been shown to be 1.5% to 5.3% postoperatively.[4,7] Recent studies have highlighted concerns about the potential increased risk of patellar fractures owing to the patellar morphology at the superior pole.[4,15]

The purpose of this study was to quantify the maximum load to fracture in patellae from which BPTB and BQT autografts have been harvested for ACL reconstruction in a cadaveric model. The hypothesis of this study was that load to fracture would not be significantly different in patellae with a BQT graft harvest site versus a BPTB graft harvest site.

Methods

A total of 46 fresh-frozen cadaveric adult human patellae (aged 65 ± 16 years; 24 female specimens, 17 male specimens, and 6 specimens of unknown sex) were obtained from national tissue banks (Anatomy Gifts Registry, Hanover, MD, and Science Care, Phoenix, AZ) after institutional review board approval. Specimens were isolated and evenly divided into 2 groups: BPTB harvest group and BQT harvest group. There was a similar sex distribution between the groups, and the groups were matched on donor age (±5 years) (Table 1). Prior to testing, computed tomography scans of each patella were taken and 3-dimensional reconstructions were used to calculate overall bone mineral density (BMD) (Mimics Medical; Materialise, Leuven, Belgium). Reconstructions were imported into Geomagic Wrap (3D Systems, Morrisville, NC) to measure patellar height, width, and thickness. The patellar coordinate system was defined with the mediolateral axis passing through the center of the lateral ridge at the extreme of the lateral facet and through the center of the medial ridge at the extreme of the medial facet.[16] The superoinferior axis was defined as perpendicular to the mediolateral axis, passing through the distal-most point of the patella, with the anteroposterior axis defined as being perpendicular to the other 2 axes. Height was defined as the distance from the most superior point of the articular surface to the most inferior point of the articular surface. Width was similarly defined as the distance from the most medial point of the articular surface to the most lateral point of the articular surface. The thickness of the patella was calculated through multiple steps. First, the midpoint of the most medial and lateral points was determined. Then, points were identified along both the most medial and lateral edges of the articular surface. A plane was fit to these points, and vectors were created perpendicular to the plane through the medial-lateral midpoint crossing the anterior and posterior aspects of the patella. The distance from the location at which the vector intersected the articular surface to the point at which the vector intersected the anterior surface was calculated and used to define the patellar thickness. This vector defined the anteroposterior axis.

Graft harvest was conducted using the same technique for both BPTB and BQT grafts. The midline of the patella was determined as 50% of the distance between the most medial and lateral aspects of the patella using the coordinate system described earlier. The point was marked on the patella with a surgical marker. Similarly, 50% of the height of the patella was determined and marked. To define the extent of the harvest site, 5 mm was marked to either side of the midline. A sagittal saw was used to create the cuts, and an osteotome was used to elevate the bone plug from the patella. The bone plugs were 10 mm wide, 6 mm deep, and 50% of the superoinferior length of the individual patellae, similar to the criteria reported in Fu et al.[4] (Fig 1). All grafts were harvested by a sports medicine fellowship—trained orthopaedic surgeon (K.S.).

Each patella was tested on a custom jig in a 3-point bend using a servo-hydraulic frame (MTS 858; MTS, Eden Prairie, MN) with a 5,000-N load cell. The patella was placed such that the anterior surface of the

Table 1. Demographic Data, Patellar Measurements, and Testing Outcome Measures for All Specimens Tested

	Patellar Tendon Block	Quadriceps Tendon Block	*P* Value
Maximum load to fracture, kN	5.0 ± 2.3 (8.3-10)	5.1 ± 2.6 (6.0-9.9)	.91
Fracture through harvest site, n	20 of 23	18 of 23	
Age, yr	66 ± 16 (28-85)	64 ± 17 (28-85)	.73
Sex, n			.94
Female	13	11	
Male	9	8	
Unknown	1	4	
Bone density, mg/cm^3	638 ± 86 (523-798)	623 ± 81 (462-778)	.59
Patellar thickness, mm	21.1 ± 1.8 (16.8-24.8)	21.7 ± 1.7 (17.0-25.0)	.29
Cut depth as % of patellar thickness	27 ± 5 (18-36)	31 ± 8 (15-47)	.09
Patellar width, mm	45.3 ± 3.4 (37.5-51.0)	44.5 ± 3.7 (36.2-50.0)	.45
Patellar height, mm	43.2 ± 3.9 (34.6-50.3)	42.8 ± 4.1 (34.4-48.7)	.77

NOTE. Data are presented as mean ± standard deviation (range) unless otherwise indicated.

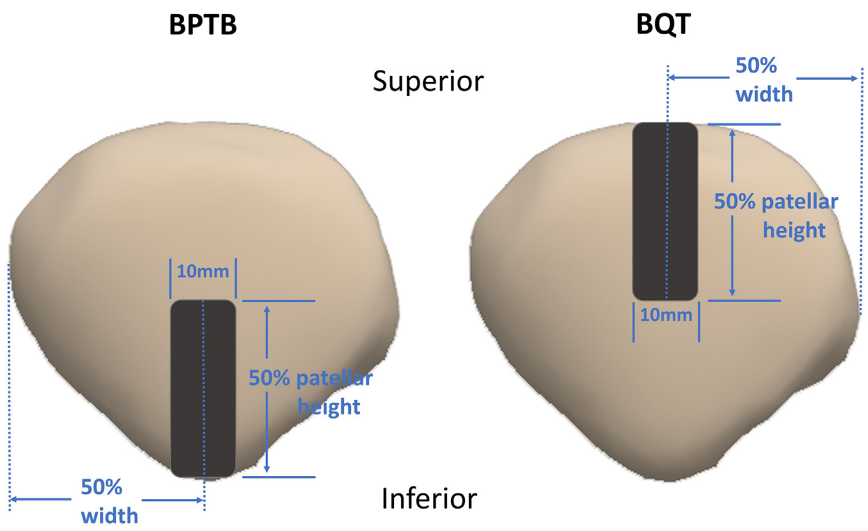

Fig 1. Graft harvest sites, created at midline of patella, measuring 10 mm in width and extending through 50% of patellar height.[4] (BPTB, bone–patellar tendon–bone; BQT, bone-quadriceps tendon.)

patella rested on the lower supports and was aligned such that the medial and lateral aspects of the patella were in line with the supports and the superoinferior axis was parallel to the supports. Sutures were attached to the medial and lateral aspects of the patella and secured to posts on either side of the 3-point bend setup to ensure that the patella did not slide or rotate during testing. A 50-mm-diameter cylinder applied load with the flat aspect of the cylinder contacting the patellar ridge. The diameter of the cylinder was chosen to ensure that the patellar ridge would be contacted regardless of patellar laterality or ridge location. Specimens were tested in displacement control using a ramp to failure with an actuator displacement rate of 100 mm/s for 5 mm (Fig 2). This setup was used to represent a worst-case scenario in which the cut anterior surface was under tension, during a direct impact, simulating a common mechanism of patellar fracture with a combined impact on a flexed knee with quadriceps contraction.[17] The presence of fracture, fracture location, and maximum load to fracture were recorded. Specimens that did not fracture remained on the supports during testing.

Statistical Analysis

The Student *t* test was used to compare donor demographic characteristics, patellar measurements, and maximum load to fracture, with the level of significance set at $P < .05$. Normal distribution of data was confirmed using the Shapiro-Wilk test. All data are reported as mean ± standard deviation. Pearson correlations were used to determine whether maximum load was affected by bone density or patellar morphology, with the level of significance set at $P < .05$. The sample size was calculated based on data from Moholkar et al.,[18] with $\beta = 0.8$ and $\alpha = 0.05$.

Results

No significant differences in bone density, patellar thickness, cut depth as a percentage of thickness, patellar width, or patellar height occurred between the 2 groups (Table 1). Fracture through the harvest site was observed in 20 of 23 BPTB specimens (87%) and 18 of 23 BQT specimens (78%). Fractures through the harvest site consisted of a combination of a longitudinal fracture line through the harvest site to the superior aspect of the patella and a longitudinal fracture line through the harvest site with either a transverse or Y-shaped extension at the top of the cut (Fig 3). Of the specimens that did not fracture through the harvest site, 2 BPTB specimens and 3 BQT specimens fractured through the medial articular surface. The remainder of the specimens did not fracture (1 BPTB specimen and 2 BQT specimens). Regarding the specimens that fractured, there was no significant difference in maximum load to fracture between BPTB specimens and BQT

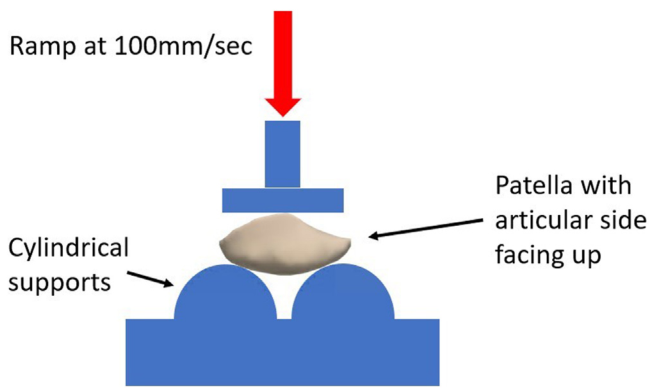

Fig 2. Test setup showing placement of patella between 2 support structures, with load applied through a solid cylindrical platen attached to load cell.

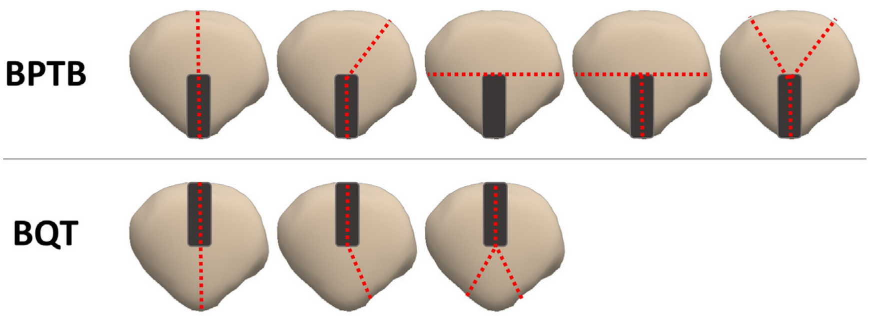

Fig 3. Fracture lines observed after testing. The gray rectangles represent bone cuts, and the red dotted lines represent fracture lines, with the exact location varying with each specimen. (BPTB, bone–patellar tendon–bone; BQT, bone-quadriceps tendon.)

specimens (5.0 ± 2.3 kN and 5.1 ± 2.6 kN, respectively; $P = .91$) (Fig 4).

For BPTB harvest, no correlation was found between maximum load to fracture and bone density ($P = .57$), patellar thickness ($P = .57$), cut depth as a percentage of thickness ($P = .71$), patellar width ($P = .43$), or patellar height ($P = .45$). For BQT harvest, a positive correlation was observed between maximum load to fracture and bone density ($P = .03$, $R^2 = 0.25$). There was a negative correlation between maximum load to fracture and patellar height ($P = .02$, $R^2 = 0.22$) (Fig 5). No correlation between maximum load to fracture and patellar thickness ($P = .18$), cut depth as a percentage of thickness ($P = .18$), or patellar width ($P = .35$) was found for BQT harvest.

Discussion

The most important finding of this study was that no difference in maximum load to fracture was observed between the BPTB and BQT harvest sites, suggesting that bone block taken from the superior pole of the patella during ACL reconstruction surgery does not increase the risk of patellar fracture. The patellar fracture incidence has been more broadly evaluated after ACL reconstruction with BPTB autograft. The overall fracture rate after BPTB procedures is low; however, the implications for rehabilitation and outcomes are substantial. A cadaveric study showed that the central patellar ridge deviates medially, indicating that harvesting from this region for BPTB may reduce the risk of fracture.[19]

Prior clinical studies have shown similar fracture rates between BPTB and BQT autograft harvest.[1,7,20,21] However, a study by Fu et al.[4] found that the incidence of patellar fractures was 3.5% intraoperatively and 8.8% at 2 years after ACL reconstruction with QT autograft. The potential effects of the location and depth of the harvest site have been explored.[22,23] Harvesting the bone plug from the lateral portion of the patella[22] and a depth of harvest greater than 50% were associated with fracture.[23] Moreover, Ferrer et al.[15] examined morphologic parameters associated with patellar fracture after QT autograft harvest. They compared non-fractured and fractured patellar surface models created based on patient data and found that the relative depth of the bone block harvest site in the non-fractured patella was significantly less than that in the fractured patella. These findings suggested that surgeons avoid exceeding 30% of the total patellar thickness at harvest, rather than harvesting at a fixed depth. Although we did not find a correlation with the cut depth as a percentage of patellar thickness, the cuts were below the 50% threshold suggested by Negrin et al.[23] and were on average around 30% of the thickness. Although no significant difference was associated with patellar width in this study, patellar height was associated with an increased fracture risk for the BQT specimens, thus indicating the implications of patellar morphology on fracture potential. The association between both bone density and patellar morphology and the load to fracture for BQT harvest suggests that there are risk factors that may be modified to decrease the already low rates of fracture associated with BQT autograft. Further study examining patellar morphology and bone cut placement relative to the patellar ridge may

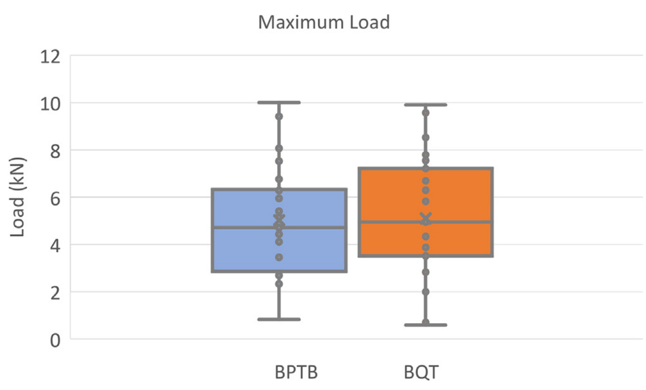

Fig 4. Maximum load to fracture. No significant difference was observed between the 2 groups. For each group, the horizontal lines of the box represent the first quartile, median, and third quartile of the data. The whiskers show the minimum and maximum values. The actual values are represented by cirles with the average value represented with an 'x'. (BPTB, bone–patellar tendon–bone; BQT, bone-quadriceps tendon.)

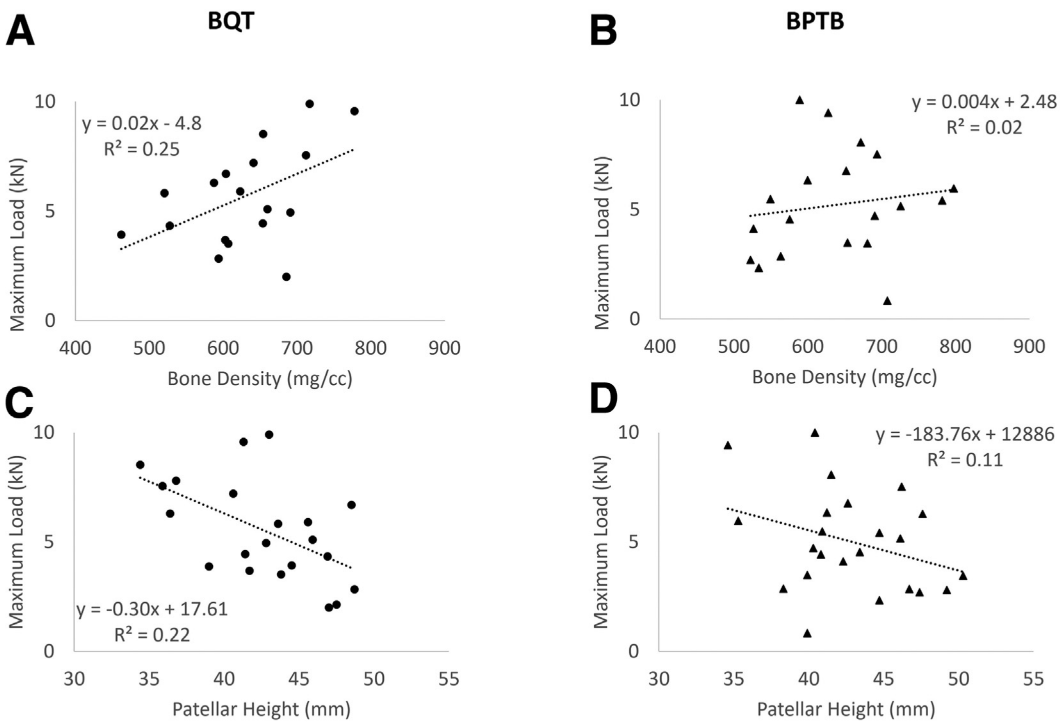

Fig 5. For bone-quadriceps tendon (BQT) harvest-site specimens, a positive correlation between load to fracture and bone density was observed (A) whereas a negative correlation between load to fracture and patellar height was evident (C). By contrast, for bone–patellar tendon–bone (BPTB) harvest-site specimens, there was not a significant correlation between load to fracture and bone density (B) or patellar height (D). Circles are used to represent BQT data points, triangles represent BPTB data points, and dotted lines show the linear correlation between the 2 factors in the graph.

guide the optimal harvest location on the patella to reduce fracture risk.

Limitations

This study has several limitations. The mean age of the specimens was higher than the age of patients typically undergoing ACL reconstruction (66 ± 16 years in BPTB group and 64 ± 17 years in BQT group). However, there was no significant difference in BMD between the 2 groups. Additionally, the testing conditions simulated a postoperative fracture with a direct impact under tension; however, the study did not account for fractures with only indirect mechanisms involving eccentric loading or perioperative fractures. Even with this limitation, the types of fractures (transverse, Y-shaped, and vertical) that occurred are consistent with those found in the clinical setting.[1,2,7,21,24] Additionally, this is a cadaveric study, which does not directly simulate real-world clinical conditions associated with postoperative patellar fracture.

Conclusions

The location of the BPTB or BQT autograft harvest site did not significantly affect patellar load to fracture in a cadaveric model.

Disclosure

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