

Article

The Influence of Bone Bruises on Bone Tunnel Enlargement Regarding ACL Rupture

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Featured Application: The close proximity of bone bruises (BBs) to the bone tunnel created during ACL reconstruction in the femur may contribute to the occurrence of BTE as an undesired side effect. Determining the spatial position of the BB in regard to the location of the femoral tunnel by imaging during preoperative planning may reduce BTE incidence and the risk of not achieving knee stability.

Abstract: **Purpose:** The purpose was to determine the impact of the size of bone bruises (BBs) on bone tunnel enlargement (BTE) occurrence. **Materials and methods:** Twenty-four (24) patients who underwent anterior cruciate ligament reconstruction (ACLR) were included in this retrospective study. The measurements of BBs based on the initial MRI scan, bone tunnel size based on the control MRI scan, and the spatial determination of BB in relation to the bone tunnel location were evaluated. To analyze the relationship between BBs and BTE in homogeneous groups regarding the time from injury to ACLR (t(I-S)), the largest subgroup B (n = 15), in which t(I-S) was 31 to 60 days, was isolated for further investigation. **Results:** Based on subgroup B, a weak correlation (r = 0.33) existed between the BB volume and BTE size in the femur and tibia. Considering the relationship between the distance from the BB to the bone tunnel in the femur (f-l) and its enlargement (Δf_d), there was a moderate and statistically significant (p < 0.05) negative correlation (r = −0.64). The correlation between those parameters was even stronger (r = −0.77) in subgroup B (time interval between injury and surgery ranged from 31 to 60 days). **Conclusions:** A retrospective analysis of MRI data in patients after ACL reconstruction surgery showed a relevant association between the distance from the BB to the bone tunnel and BTE in the femur. The relationship was not confirmed in the tibia.

Keywords: bone bruises; anterior cruciate ligament reconstruction; bone tunnel enlargement



Citation: Rajca, J.; Gzik, M.; Ficek, K. The Influence of Bone Bruises on Bone Tunnel Enlargement Regarding ACL Rupture. *Appl. Sci.* **2021**, *11*, 2482. <https://doi.org/10.3390/app11062482>

Academic Editor: Gabi Chaushu

Received: 2 February 2021

Accepted: 8 March 2021

Published: 10 March 2021

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1. Introduction

Anterior cruciate ligament (ACL) ruptures resulting from an indirect mechanism of injury are associated with sport participation and general military and physical activity. The common surgical procedure, ACL reconstruction (ACLR), has demonstrated good clinical outcomes resulting in the restoration knee stability but is associated with complications, e.g., bone tunnel enlargement (BTE). The cause of BTE remains unclear, and two main types of factors are suspected of being involved—mechanical and biological factors [1–5]. Mechanical factors such as tunnel placement, the number of tunnels, the fixation method, the drilling technique used following bone necrosis, and the aggressiveness of the rehabilitation process may be involved [2,6–12]. Biological factors are related to the graft healing process in the emerged bone tunnel, which is always influenced by the presence of synovial fluid and inflammatory state mediators [1,11]. The clinical importance of BTE is not yet well understood. Despite research having been conducted on BTE, there is a lack

of studies on the correlation between BTE and surgical success [13–19]. It is possible that BTE is an early sign of graft failure resulting in a future renewed lesion [9], as evaluated by radiographs and arthrometry. BTE after six months may suggest poor graft healing, which can lead to screw loosening and joint instability [18]. Nevertheless, BTE occurrence should always be considered seriously in regard to revision surgeries, as the probability of surgery failure increases in the presence of massive BTE [20,21].

Currently, magnetic resonance imaging (MRI) is crucial in detecting ACL rupture and determining the mechanism of injury, despite its static nature. In addition to complete or partial ACL rupture, concomitant injuries such as tears of the meniscus or other ligaments or muscle and bone damage have been described [22]. ACL tears are linked with large external loads in combination with ligament injury susceptibility in the presence of unfavorable weight distribution, leading to rapid impact to the tibia and femur, and the generated forces transfer through the cartilage to the bone itself. This process leads to visible cancellous bone edema in diagnostic imaging [23] (Figure 1). The main cause of bone bruises (BBs) is direct contact of the articular surfaces influenced by tangent tightening fusion generated during a ligament tear [24]. Bone contusion leads to a large spectrum of types of bone degeneration, including bleeding, fractures, and trabecular bone microcompression fractures [25–27].

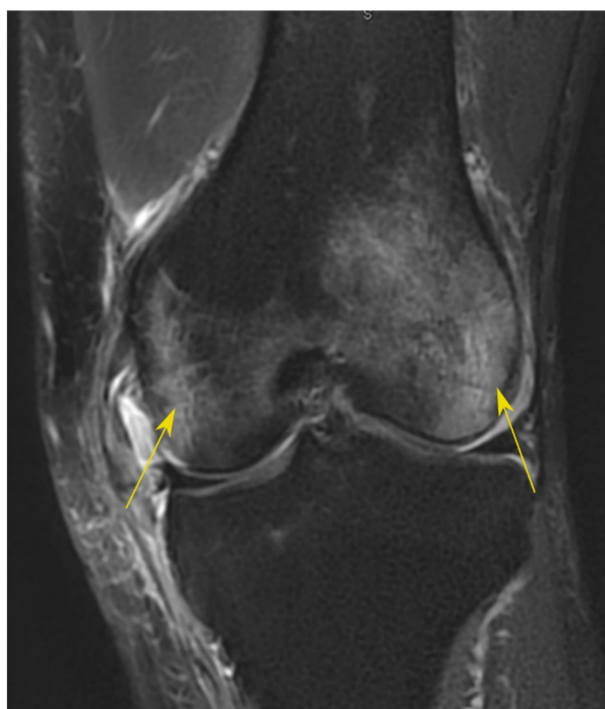


Figure 1. Magnetic resonance image of an extensive bone bruise in femur associated with anterior cruciate ligament injury.

MRI scans performed after acute ACL tears in patients allow us to detect tibial and femoral BBs, which occur in more than 80% of ACL rupture cases [23,28–32]. Subchondral injuries, as well as bone marrow edema, are widely recognizable in MR images and are often considered BBs. Nevertheless, their size and the potential effects of their occurrence, such as graft healing in bone tunnels after ACLR, have not been studied. Multiple studies in the scientific literature describing the influence of subchondral and cancellous bone injuries on the knee joint (its structure and function) are limited to degenerative aspects (osteoarthritis) [33,34]. Until now, researchers have not studied extensively the possible effect of BBs on the surgical success of ACLR; hence, there is a lack of imaging studies that can be used to explicitly define whether and if so, in what range the bone tunnels drilled during ACLR pass through the areas of the most common cancellous bone injuries or close to them. Recent findings indicate that the presence of bone marrow edema correlates

with the prognosis at mid- and long-term follow-up [35]. Furthermore, not only traumatic fractures of trabeculae, which may occur due to damage accumulation in the form of BBs, but also controlled (iatrogenic) bone fractures made to create tunnels (i.e., the partial removal of cortical and cancellous bone) for graft placement are types of fractures that appear in the bone tissue in cases treated by ACL injury and surgery. Therefore, the surroundings of the bone tunnel may be insufficient to withstand micromovements of the graft, thereby resulting in BTE.

The aim of the paper was to determine the impact of the size of BBs on BTE appearance based on MR imaging. The hypothesis is that BBs, which appear in the femur and tibia, negatively affect the bone tunnel, causing BTE.

2. Materials and Methods

Based on a review of the medical records of patients surgically treated for ACL tears incurred while participating in various sport activities between 2010 and 2017, twenty-four patients (24) were considered for the study. The main criteria for inclusion in this retrospective study were as follows: a specific time of injury (year, month, day), MRI data collected no later than 50 days after injury, no history of ACLR, and follow-up MRI data. The patients underwent ACLR with the use of the gracilis and semitendinosus tendons (STGR). The transportal femoral tunnel drilling method for endoscopic ACLR was used. Femoral fixation was achieved using an EndoButton (Smith and Nephew Inc., Andover, MA, USA), and tibial fixation was achieved by using a Biosure PEEK (Smith and Nephew Inc., Andover, Massachusetts) interference screw. All patients underwent a standardized postoperative rehabilitation protocol one week after surgery. Demographic data are presented in Table 1.

Table 1. Demographic data.

	n	Age $\pm$ SD [Years]	BMI $\pm$ SD	Knee		Time from Injury to MRI $\pm$ SD [Days]	Time from Injury to Surgery $\pm$ SD [Days]	Graft Thickness $\pm$ SD [mm]	Period of Follow-Up [Days]
				right	left				
STGR	24	29 $\pm$ 9	23.53 $\pm$ 3.00	7	17	10 $\pm$ 9	50 $\pm$ 43	7.8 $\pm$ 0.8	320
Females	9	34 $\pm$ 12	22.33 $\pm$ 1.68	2	7	-	-	-	-
Males	15	25 $\pm$ 6	24.25 $\pm$ 3.42	5	10	-	-	-	-

STGR—semitendinosus tendons.

2.1. Measurements of Bone Bruises

All advanced image analyses were carried out in 3D medical image processing software (Mimics Innovation Suite, Materialise, Leuven, Belgium). The BBs were measured for each patient on coronal cross-sections (Fat-Saturated Proton Density (FS-PD) sequence) of both the femur and tibia. The upper and lower thresholds for BBs were created based on a grayscale. For each bone (femur and tibia), three cross-sections that were characterized as having the largest healthy (meaning unimpaired) area of bone tissue were chosen. With this approach, the region of interest (ROI) was defined (Figure 2A). Information about the density distribution within each ROI was exported to a spreadsheet, and a grayscale value that 99% of the pixels contained in the ROI were larger than was determined. After the lower values were discarded, the arithmetic mean and standard deviation were calculated [36]. The upper threshold (T_U) for healthy bone tissue in the whole volume was determined by the formula:

$$T_U = \bar{x} + SD \quad (1)$$

where $\bar{x}$ —is an average and SD—is a standard deviation.

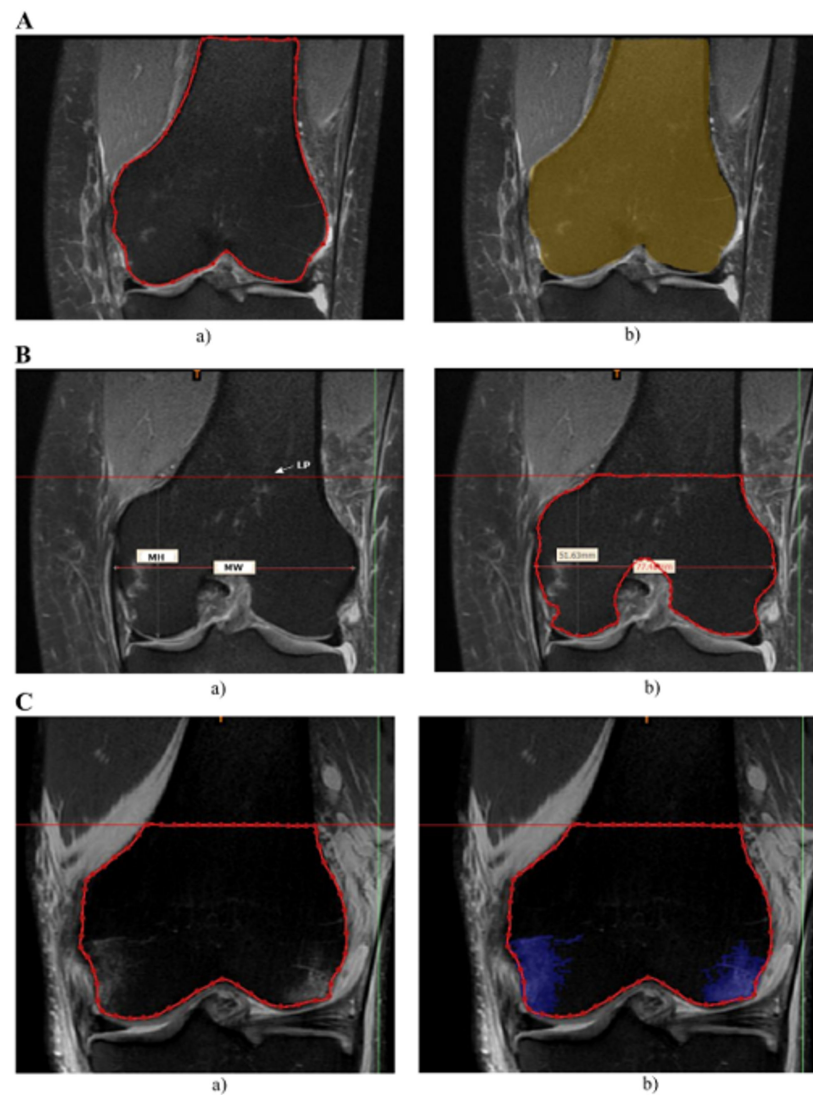


Figure 2. (A) Region of interest (ROI) for the femur: (a) the edges of the ROI and (b) the ROI mask. (B) Methodology of determining the total volume (TVI): (a) measurement of maximum width (MW) and maximum height (MH) and (b) determination of the ROI in TVI. (C) Bone bruise (BB) segmentation process: (a) coronal cross-section of the femur with BBs and (b) coronal cross-section of the femur with segmented BBs.

The value of T_U for healthy bone increased by one was the lower threshold (T_L) for the BBs. The upper threshold for the BBs was 255 (in 8-bit integer value 255 is white).

2.2. Determining Total Bone Volume

To determine the total volume of bone (TVI) separately for the femur and tibia, the maximum width (MW) of the distal femur and proximal tibia were indicated, and the BB measurements were made with respect to the total volume. This value was used to determine the maximum height (MH) and hence the TVI according to the following formula:

$$MH = \frac{MW}{w} [mm] \quad (2)$$

$$TVI = MW \times MH \times slice\ thickness [mm^3] \quad (3)$$

where $w = 1.5$, which is a constant coefficient that was adopted based on a review of imaging data of patients included in the retrospective study and coronal plane dimensions.

The height was always measured from the medial side of the knee joint: from the top of the medial condyle for the femur and from the most concave place on the articular surface for the tibia. The line perpendicular to the *MH* (*LP*) remained constant on all MRI slices, delineating the *TVI* (Figure 2B).

2.3. Segmentation of BB

For the *TVI* volume, the *BB* was segmented for the femur and tibia by the thresholding method and the region growing method (in addition to the intensity criteria established in the previous steps, the pixel had to belong to the neighborhood of the pixel already included in the given area) (Figure 2C).

The percentage of *BBs* in *TVI* was calculated according to the formula:

1. in femur:

$$f - \frac{BB}{TVI} = \frac{fBB}{fTVI} \times 100\% \quad (4)$$

2. in tibia:

$$t - BB/TVI = \frac{tBB}{tTVI} \times 100\% \quad (5)$$

2.4. Measurement of Bone Tunnel

To assess the size of BTE after ACLR, the MRI data collected after surgery were analyzed. To accurately determine the dimensions of the bone tunnel, the MRI images were resliced so that the long central axis of each image corresponded to the exact center of the bone tunnel (axial cross-sections perpendicular to the bone tunnel's axis of symmetry). New stacks of images were generated separately for the femur and tibia. The entire tunnel length was divided into three equal parts (Figure 3a). In each part, the largest diameter of the tunnel was defined (d_1 —diameter in part closest to the articular surface, d_2 —diameter in the middle part, d_3 —diameter in the distal part of the tunnel) by adjusting the diameter of the circle (Figure 3b) [37]. In place of the largest diameter, the area was also measured by fitting the ellipse (cross-sectional area (CSA) parameter) (Figure 3c).

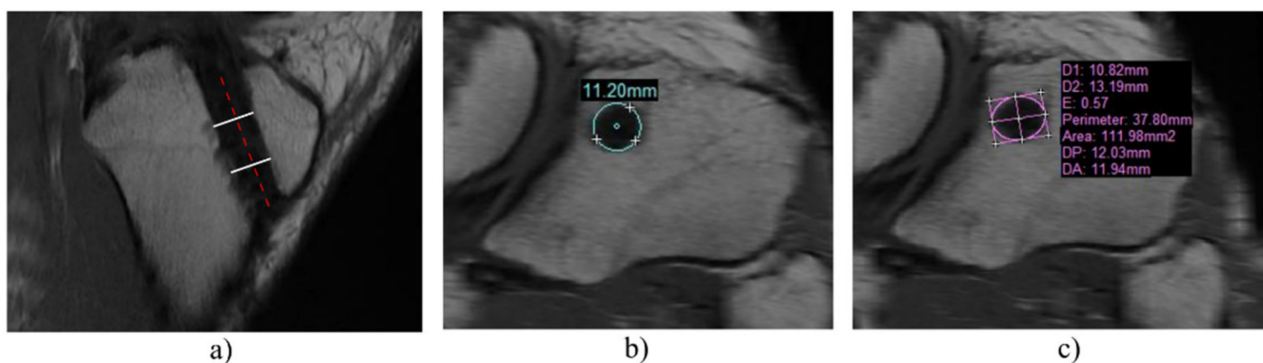


Figure 3. The method of measuring the bone tunnel: (a) the tunnel was divided into three parts, (b) the largest diameter of the circle was determined, and (c) the tunnel area was determined.

Based on measurements of the bone tunnel, the percentage increases in diameter and surface area (average of three measurements) were calculated according to the following formulas:

- percentage increase in tunnel diameter in the femur and tibia:

$$\Delta fd = \frac{(\sum d_i/n) \times 100\%}{d_p} - 100\% \quad (6)$$

$$\Delta td = \frac{(\sum d_i/n) \times 100\%}{d_p} - 100\% \quad (7)$$

where Δfd —is an increase in the femur, Δtd —is an increase in the tibia, d_p —is an initial tunnel's diameter, d_i —is a value of the tunnel's diameter in a specific part of the tunnel, and n —is a sample size.

- percentage increase in tunnel area in the femur and tibia:

$$\Delta fCSA = \frac{(\sum CSA_i/n) \times 100\%}{CSA_p} - 100\% \quad (8)$$

$$\Delta tCSA = \frac{(\sum CSA_i/n) \times 100\%}{CSA_p} - 100\% \quad (9)$$

where $\Delta fCSA$ —is an increase in the femur, $\Delta tCSA$ —is an increase in the tibia, CSA_p —is an initial tunnel's area, CSA_i —is a value of the tunnel's area in a specific part of tunnel, and n —is a sample size.

The initial CSA value was calculated from the following formula for the cylinder base surface area:

$$CSA_p = \pi \left(\frac{d_p}{2} \right)^2 \quad (10)$$

2.5. Spatial Characteristics of Bone Bruises in Correlation to Bone Tunnel Location

For each patient, through segmentation, 3D models for the femur and tibia were generated. Smoothing (with equal parameters) was performed for every 3D model of bone. For the primary MRI scan, 3D models of BBs for both the distal femur and proximal tibia were generated. Based on the control MRI data, an additional 3D model of bone tunnels was obtained (Figure 4A).

In Mimics, 3D objects in the form of STL files corresponding to scans taken before and after surgery were temporarily grouped in the following order: (1) the femur before surgery and BB femur, (2) the tibia before surgery and BB tibia, (3) the femur after surgery and femoral bone tunnel, and (4) the tibia after surgery and tibial bone tunnel.

The grouped 3D models of the femur before and after surgery and the tibia before and after surgery were superimposed using the point registration algorithm. For this purpose, five points were indicated in the 3D models. The points were marked partly based on our own research (based on MRI analysis of patients from the database presented) [38] (Figure 4B).

After automatic superimposition, the 3D objects were ungrouped, and the distances between the center of mass of the bone tunnel and the center of mass of the BBs (f -l: distance in femur, t -l: distance in tibia) were measured (Figure 4C). In the event that the bone tunnel passed through the damaged area (BB), the intersection function (which creates a new object whose surface encloses the volume common to both original objects) was also used. In the results, the overlapping area of two objects represents the volume for which the bone tunnel collides with BBs ($\cap f$ —intersection of the bone tunnel and BB in the femur, $\cap t$ —intersection of the bone tunnel and BB in the tibia).

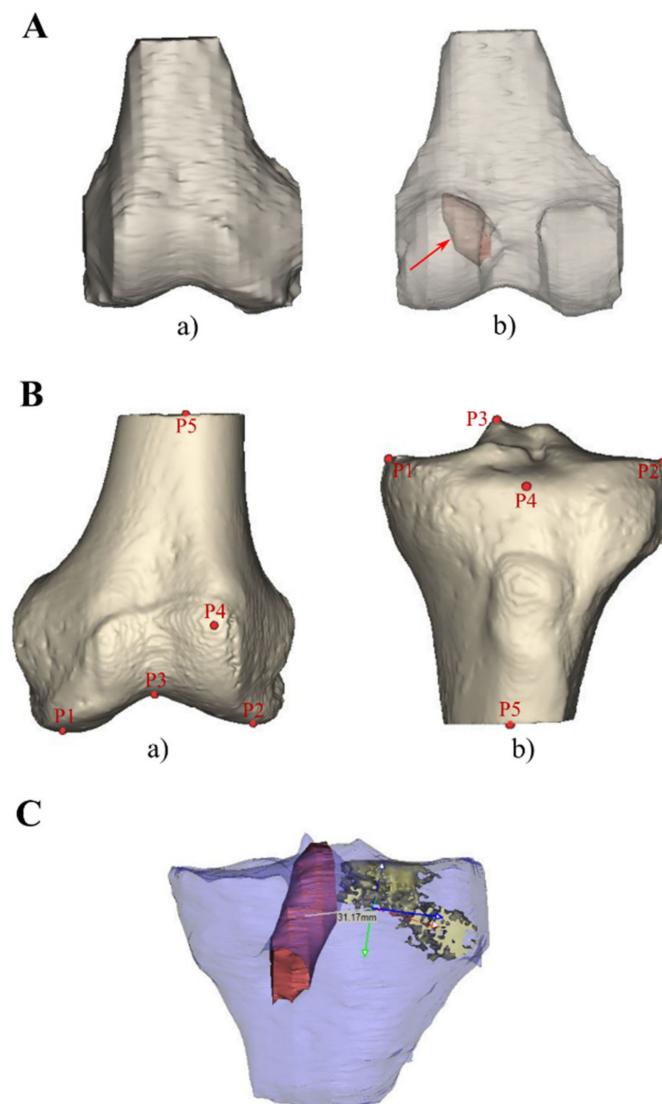


Figure 4. (A) 3D surface model of the distal femur: (a) opaque model, (b) transparent 3D model with the indicated bone tunnel (red arrow). (B) Location of the landmarks. Femur: P1—the farthest point on the medial condyle, P2—the farthest point on the lateral condyle, P3—intercondylar fossa, P4—lateral peak, P5—the center of the diaphysis. Tibia: P1—medial peak, P2—lateral peak, P3—medial intercondylar tubercle, P4—frontal peak, P5—center of the diaphysis; (C) Measurements of the distance between the center of mass of the bone tunnel and bone bruises.

2.6. Statistical Analysis

An a priori power analysis (G*Power 3.1.9.4, Faul, Erdfelder, Lang, & Buchner, 2007, Germany) was completed to calculate the number of patients needed in the STGR group to detect a Pearson's correlation coefficient of $r = 0.5$ with 80% power ($\alpha = 0.05$, two-tailed). The power analysis indicated that 29 patients would be required. The relationships between particular variables were estimated based on Pearson's correlation coefficients calculated with Statistica 13.1. (StatSoft). In consecutive analysis, to analyze the relationship between BBs and BTE in more homogeneous groups regarding the time from injury to ACLR (t(I-S)), the STGR group was divided into three subgroups: (A) t(I-S) of 0 to 30 days, (B) t(I-S) of 31 to 60 days, and (C) t(I-S) of more than 60 days. Because subgroups A and C consisted of only five and four patients, respectively, the results for subgroup B only were presented in the paper. In the paper, the correlation coefficients were interpreted as follows, which was adopted from [39]: 0.9 to 1.00—very high correlation, 0.7 to 0.9—high correlation, 0.5 to 0.7—moderate correlation, 0.3 to 0.5—low correlation, and 0.0 to 0.3—negligible correlation.

Correlation analysis was performed between the following variables: *t(I-MRI)* (days): time between injury and the MRI scan; *t(I-S)* (days): time between injury and surgery, *f-BB/TVI* (%): volume of BBs in a defined volume of the femur, *t-BB/TVI* (%): volume of BBs in a defined volume of the tibia, $\Delta f d$ (%): magnitude of change in the bone tunnel diameter in the femur, $\Delta t d$ (%): magnitude of change in the bone tunnel diameter in the tibia, $\Delta f CSA$ (%): magnitude of change in bone tunnel area in the femur, $\Delta t CSA$ (%): magnitude of change in the bone tunnel area in the tibia, *f-l* (mm): distance between the center of mass of the femoral bone tunnel and center of mass of the BB, *t-l* (mm): distance between the center of mass of the tibial bone tunnel and the center of mass of the BB, $\cap f$ (mm³): intersection of the femoral bone tunnel and BB, and $\cap t$ (mm³): intersection of the tibial bone tunnel and BB.

3. Results

In the STGR group, a BB in the femur was not observed in six patients or in the tibia in one patient. Detailed results including the correlation coefficients between variables are presented in Table 2.

Table 2. Results of correlation analysis for the STGR group. Correlation coefficients are statistically significant at $p < 0.05$ (in red). *t(I-MRI)*—time between injury and the MRI scan; *t(I-S)*—time between injury and surgery; *f-BB/TVI* (%): volume of BBs in a defined volume of the femur, *t-BB/TVI* (%): volume of BBs in a defined volume of the tibia, $\Delta f d$ (%): magnitude of change in the bone tunnel diameter in the femur, $\Delta t d$ (%): magnitude of change in the bone tunnel diameter in the tibia, $\Delta f CSA$ (%): magnitude of change in bone tunnel area in the femur, $\Delta t CSA$ (%): magnitude of change in the bone tunnel area in the tibia, *f-l* (mm): distance between the center of mass of the femoral bone tunnel and center of mass of the BB, *t-l* (mm): distance between the center of mass of the tibial bone tunnel and the center of mass of the BB, $\cap f$ (mm³): intersection of the femoral bone tunnel and BB, and $\cap t$ (mm³): intersection of the tibial bone tunnel and BB.

	<i>t(I-MRI)</i>	<i>t(I-S)</i>	<i>f-BB/TVI</i>	<i>t-BB/TVI</i>	$\Delta f d$	$\Delta t d$	$\Delta f CSA$	$\Delta t CSA$	<i>f-l</i>	<i>t-l</i>	$\cap f$	$\cap t$
<i>t(I-MRI)</i>	1.00	-	-	-	-	-	-	-	-	-	-	-
<i>t(I-S)</i>	-	1.00	-	-	-	-	-	-	-	-	-	-
<i>f-BB/TVI</i>	0.02	-	1.00	-	-	-	-	-	-	-	-	-
<i>t-BB/TVI</i>	0.10	-	-	1.00	-	-	-	-	-	-	-	-
$\Delta f d$	-	0.01	0.25	-	1.00	-	-	-	-	-	-	-
$\Delta t d$	-	0.00	-	0.25	-	1.00	-	-	-	-	-	-
$\Delta f CSA$	-	0.03	0.33	-	-	-	1.00	-	-	-	-	-
$\Delta t CSA$	-	0.02	-	0.33	-	-	-	1.00	-	-	-	-
<i>f-l</i>	-	-	-	-	-0.64 ($p = 0.010$)	-	-0.59 ($p = 0.020$)	-	1.00	-	-	-
<i>t-l</i>	-	-	-	-	-	-0.40	-	-0.42	-	1.00	-	-
$\cap f$	-	-	-	-	0.54 ($p = 0.036$)	-	0.46	-	-	-	1.00	-
$\cap t$	-	-	-	-	-	0.05	-	0.01	-	-	-	1.00

The outcomes indicated that the time between the injury and MRI evaluation (*t(I-MRI)*) was not related ($r > 0.3$) with the volume of BBs in the defined volume of the femur or tibia (*f-BB/TVI* and *t-BB/TVI*, respectively). There was also no correlation ($r > 0.3$) between the time from the moment of injury to ACLR (*t(I-S)*) and BTE, as assessed by $\Delta f d$, $\Delta t d$, $\Delta f CSA$, and $\Delta t CSA$. A weak correlation ($r = 0.33$) existed between the volume of BBs (*f-BB/TVI* and *t-BB/TVI*) and the size of BTE ($\Delta f CSA$, $\Delta t CSA$) in the femur and tibia.

Considering the relationship between the distance from the BB to the bone tunnel in the femur (*f-l*) and its enlargement, there was a moderate and statistically significant ($p < 0.05$) negative correlation ($r = -0.64$ for $\Delta f d$ and $r = -0.59$ for $\Delta f CSA$) and a weak negative correlation between the same parameters in the tibia ($r = -0.40$ for $\Delta t d$ and $r = -0.42$ for $\Delta t CSA$). The correlation coefficient was negative, which means that the smaller the distance between the BB and bone tunnel was, the larger the bone enlargement appeared. Five femoral and six tibial bone tunnels went directly through the BB. The correlation between

$\cap f$ and $\Delta f d$ was moderate ($r = 0.54$) and statistically significant ($p < 0.05$), and that between $\cap f$ and $\Delta f CSA$ was weak (but close to the threshold for a moderate correlation: $r = 0.46$). The correlation between the same parameters in the tibia was negligible.

The results of the investigated correlations in subgroup B (the time interval between injury and surgery ranged from 31 to 60 days) are presented in Tables 3 and 4. We observed a significant increase in the correlation coefficients between f -BB/TVI and $\Delta f d$, and between f -BB/TVI and $\Delta f CSA$, which increased from 0.25 and 0.33 to 0.56 and 0.66, respectively (Table 3). The correlation coefficients between t -BB/TVI and $\Delta t d$, and between t -BB/TVI and $\Delta t CSA$, also increased from 0.25 and 0.33 to 0.32 and 0.36, respectively (Table 4). Regarding the relationship between f -I and $\Delta f d$, we observed an increase in Pearson's coefficient from -0.64 to -0.77 , which can be interpreted as a strong negative correlation (Table 3). The correlation coefficient between t -I and $\Delta t d$, and between t -I and $\Delta t CSA$, increased from -0.40 and -0.42 to -0.53 and -0.49 , respectively (Table 4). The boxplots presented in Figure 5 show the tendency of bone tunnel widening at the tunnel entrance (f -d1).

Table 3. Results of correlation analysis for the femur for $t(I-S)$ = from 31 to 60 days. Correlation coefficients are statistically significant at $p < 0.05$ (in red).

	Mean	SD	f -BB/TVI	$\Delta f d$	$\Delta f CSA$
f -BB/TVI	4.53	4.46	1.00	-	-
$\Delta f d$	41.95	18.17	0.56	1.00	-
$\Delta f CSA$	115.95	55.28	0.66 ($p = 0.03$)	0.95 ($p = 0.00$)	1.00
			f -I	$\Delta f d$	$\Delta f CSA$
f -I	22.82	7.01	1.00	-	-
$\Delta f d$	50.24	15.29	-0.77	1.00	-
$\Delta f CSA$	146.87	48.48	-0.59	0.92 ($p = 0.01$)	1.00

Table 4. Results of correlation analysis for the tibia for $t(I-S)$ = from 31 to 60 days. Correlation coefficients are statistically significant at $p < 0.05$ (in red).

	Mean	SD	t -BB/TVI	$\Delta t d$	$\Delta t CSA$
t -BB/TVI	11.76	6.18	1.00	-	-
$\Delta t d$	59.20	20.25	0.32	1.00	-
$\Delta t CSA$	176.86	75.93	0.36	0.96 ($p = 0.00$)	1.00
			t -I	$\Delta t d$	$\Delta t CSA$
t -I	28.83	8.83	1.00	-	-
$\Delta t d$	59.20	20.25	-0.53	1.00	-
$\Delta t CSA$	176.86	75.93	-0.49	0.96	1.00

Based on precise engineering MRI image analysis, which was carried out twice, after injury and after surgical ACLR, the assumed negative effect of BBs on the results of ACL reconstruction regarding BTE was confirmed in the femur.

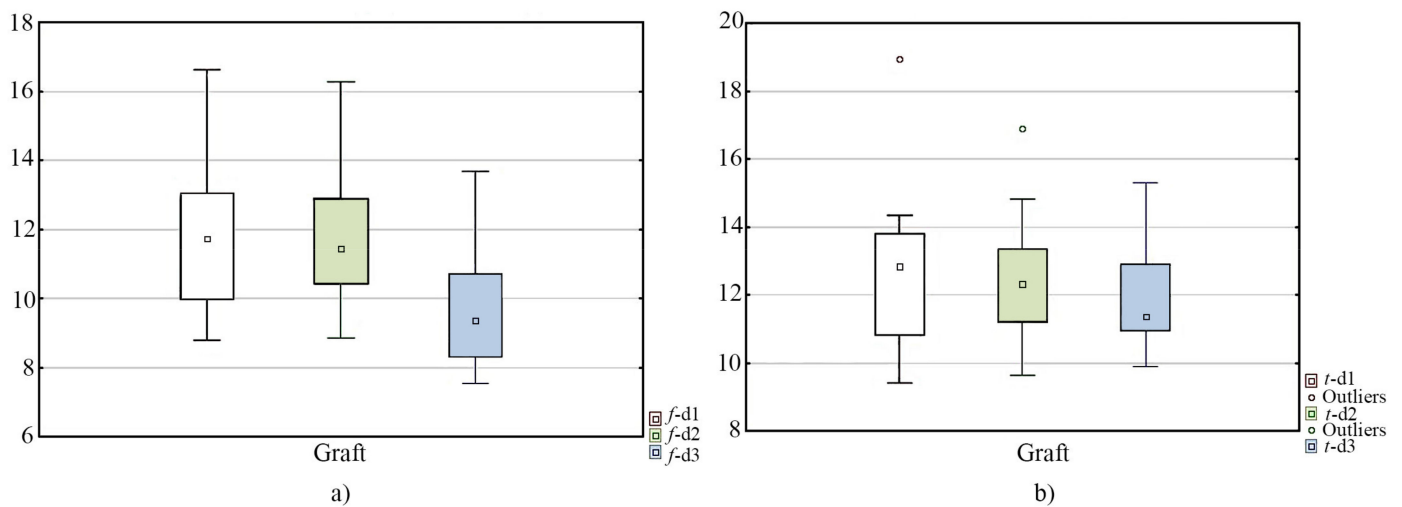


Figure 5. Boxplots showing the measurements of the diameter of (a) the femoral bone tunnel at three parts of tunnel: *f*-d1—entrance, *f*-d2—midportion, and *f*-d3—exit; (b) the tibial bone tunnel at three parts of tunnel: *t*-d1—entrance, *t*-d2—midportion, and *t*-d3—exit. Boxplot legend: the median is shown as a square in the center of the box. The top and bottom of the boxes represent the first and third quartiles, respectively. The whiskers correspond to the maximal and minimal values within the 1.5 × interquartile range (IQR). The outliers are plotted as points.

4. Discussion

The most important finding of this retrospective analysis is that the close proximity of the BBs to the bone tunnel may be a relevant factor influencing the size of BTE in the femur. The results of the retrospective analysis of MRI performed after ACL injury and after ACLR surgery demonstrated a moderate and statistically significant negative correlation between the distance from the BB to the bone tunnel and BTE in the femur, which means that decreasing the distance between the BB and the tunnel increases the size of BTE. The association was even stronger ($r = -0.77$) when the correlation coefficient was calculated in the largest subgroup of patients, in whom surgery was performed 31 to 60 days after ACL rupture. It is hypothesized that the relationship is also considerable in patients with BBs who underwent ACLR within 30 days after the injury since there is a greater likelihood that all the BB had not yet been resolved. Considering the impact of proximity of the BBs on bone tunnel size in the tibia, a close association was not confirmed, as there was a weak negative correlation. In the studied STGR group, there were five femoral and six tibial bone tunnels that directly passed through the BB. The intersection of the bone tunnel and BB (measured in mm^3) was calculated to measure to what extent the BB collides with the tunnel. The relationship between this intersection and the increase in the diameter of the tunnel ($\Delta f d$) in the femur was moderate; however, the relationship in the tibia was negligible. In our group of patients, a BB was not present in the femur in six patients or in the tibia in one patient, which is consistent with the outcomes reported by Fayad et al. [40], who studied the prevalence of BBs in the anterior, posterior, and middle aspects of the lateral and medial compartments of the tibia.

In this paper, we elucidated that because MRI is the common diagnostic tool in the examination of ACL tears, there is an opportunity to simultaneously investigate concomitant injuries such as BBs that may have an impact on ACL reconstruction success. We aimed to highlight the need for preoperative assessments of the bone environment, which constitutes support for implanted grafts and ensures proper incorporation and healing. Applying a quantitative method of measuring bone BBs in spatial relation to the bone tunnel prior to ACLR may reduce complications including BTE. In contrast to graft fixation by interference screws or EndoButton devices, bone around the tunnel is a natural material used for the fixation of transplanted tendons. Fixation develops through bone ingrowth into the tissue of the fibrovascular interface that initially forms between the outer part of the tendon and the inner bone wall [41]. In the subsequent steps, progressive mineralization of the interface

tissue appears, with bone ingrowth into the outer graft and the incorporation of the graft into neighboring bone tissue [41]. This process is influenced by many different factors and may be modified for different regions of the bone tunnels [42,43], such as the entrance, midportion, and exit [44]. To the best of our knowledge, this is the first study of its kind that highlights the influence of bone bruising on bone tunnel widening by determining the spatial locations of BBs with respect to femoral and tibial tunnels. This study provides novel data characterizing the relationship between the size of the bone tunnel after ACLR and BBs—information that is critical for improving treatment strategies for ACL rerupture.

In our study, there were no relationships between the size of the BB and the time from injury to the MRI evaluation. Previous studies [40–45] concluded that there is no consensus on the mean time after which BBs resolve after ACL tears. Bone contusions evolve over time from those showing acute, high-intensity signals to symptom resolution. Graf et al. [46], based on MR images in a group of 98 patients, indicated that bone contusions resolve within average of six weeks after injury. Bretlau et al. [47] reported that in acute knee injuries, BBs occurred in 53% of patients, and bone changes persisted in the fourth and twelfth months of follow-up in 69% and 12% of patients, respectively. On the other hand, a prospective study [45] showed that the BB volume can initially increase within the first six weeks after injury. Such a situation may be related to the extent of the injury, the size of the contusion, and other accompanying injuries, which also affect the extent of the injury. In most recent study, Kim-Wang et al. quantified the number of bone contusions and their locations observed on MRI scans of noncontact ACL-injured knee acquired within six weeks of injury [48]. They detected bone contusions in 135 of 136 patients. In our study, the mean time from injury to the MRI examination in the STGR group was 10 days (SD = 9 days), and the mean time from injury to surgery was 50 days (SD = 43 days). Hence, in some patients, BBs might resolve to some extent until ACLR is performed, particularly when the knee joint operation is postponed by the patient for personal reasons. Therefore, we divided the STGR group into three relatively homogeneous subgroups regarding the time from injury to ACLR and analyzed the most abundant subgroup B ($n = 15$). This process caused an increase in the correlation coefficients.

The long-term effects of ACLR can be objectively observed by MR imaging, including the assessment of possible BTE, which may cause loosening of the graft inside the bone tunnel, mechanical failure, and, as a result, the loss of the expected effect of the operation on the stability of the knee. Bone tunnel widening occurs predominantly within the first three months following ACLR. Most changes in the size of the femoral and tibial tunnels occur within the first six weeks after surgery [49]. The BTE etiology is multifactorial, including biomechanical components linked to grafts collected from both the patellar tendon (bone–tendon–bone method, BTB) and hamstrings, suggesting that more cases of BTE occur in patients with hamstring grafts [50]. On the other hand, Fauno and Kaalund studied fixation techniques and concluded that the position of the fixation sites and the type of fixation device are the main factors affecting the development of BTE [51]. In recent years, determining the best place to position tunnels has been discussed. Studies have shown that transtibial tunnel techniques result in a nonanatomic position of the femoral tunnel [52]. The transtibial drilling method has been increasingly replaced by the anatomic femoral tunnel method, providing translational and tensioning patterns similar to those of the native ACL and increased rotational stability [53,54]. Additionally, it has been observed that originally small tunnels are more likely to exhibit an advanced enlargement process than are originally large tunnels drilled during surgery [1]. The mean tibial BTE was significantly and inversely dependent on the original tibial bone tunnel diameter, with a correlation coefficient of -0.55 per unit ($7\text{ mm} = +1.93\text{ mm}$, $8\text{ mm} = +1.43\text{ mm}$, $9\text{ mm} = 0.83\text{ mm}$, $p = 0.007$). Thus, every additional increase (mm) in the diameter of the original tibial bone tunnel reduces the extent of tunnel widening by 0.55 mm . This study was conducted with computed tomography (CT).

The location of the BB always reflects the injury mechanism; the most common mechanism is anterior tibial translation with rotation. The link between the results such

as bone contusion and its mechanism were thoroughly described by Sanders et al. [24]. They also suggested that through the examination of the BB range and location inside the bone, clinicians will be able to understand, predict, and prevent soft tissue injuries. In 1996, Brandser et al. [55] carried out research on 74 individuals and the statistical analysis showed bone contusion, anterior translation of the tibia, and an uncovered posterior horn of the lateral meniscus to be the most useful for diagnosis. In fact, the combination of bone contusion and anterior tibial translation had a sensitivity of 82% and a specificity of 90%.

Diagnostic assessments for ACL tears may involve subjective (patient's subjective feeling about knee instability) and objective evaluations (such as MRI or arthrometry evaluations). Additionally, objective assessments can be divided into static (MRI) and dynamic (arthrometry, Lachman test, anterior drawer test) evaluations. It must be mentioned that arthrometers measure knee ligament laxity, and although the ACL is generally considered the primary knee stabilizer, several additional structures (anterolateral complex of the knee, collateral ligaments, menisci and their capsular attachments, posterolateral corner structures) also play key roles in knee stability [56].

Concerning clinical relevance, the findings of the current study should direct the attention of orthopedic specialists to BBs in close proximity to the bone tunnel created during ACL reconstruction in the femur due to the fact that they may contribute to the occurrence of BTE. Furthermore, determining the spatial position of the BB relative to the location of the femoral tunnel by MR imaging during preoperative planning may reduce BTE incidence and the risk of compromising knee stability.

Limitations

This study has several limitations. To draw a solid conclusion, it is necessary to conduct a study with a larger sample size. The main limitation is the nonuniform time interval between the surgical procedure and control MRI, which was caused by the retrospective nature of the study. Depending on the medical indications or postoperative complications, MRI scans were performed in the STGR group from 62 days to 6 years after ACL reconstruction (average interval of 320 days after surgery). Regarding the short follow-up period, it should be noted that according to a previous paper [49], most changes in the size of both the femoral and tibial tunnels appear within the first six weeks after ACLR. Additionally, there was a lack of standardized scanning protocols since the patients were often examined by MRI in various diagnostic imaging facilities; however, the patients were tested in magnetic fields with strength values 1.5 tesla or higher.

5. Conclusions

A retrospective analysis of MRI data from patients after ACL reconstruction surgery showed there is an association between the distance from the BB to the bone tunnel and BTE in the femur. The relationship was not confirmed in the tibia.

Author Contributions: Conceptualization, J.R. and K.F.; methodology, J.R.; investigation, J.R., M.G., writing—original draft preparation, J.R. and K.F. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: This study protocol was not reviewed by an institutional review board due to retrospective nature of the study.

Informed Consent Statement: Patient consent was waived due to retrospective nature of the study.

Data Availability Statement: The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflict of interest.

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