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Bone–patellar tendon–bone allografts are safe and effective grafts for anterior cruciate ligament one-stage revision: A consecutive series of 38 patients with at least 2 years of follow up

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ABSTRACT

Background: Rupture of the anterior cruciate ligament is one of the most common injuries in sports. Although primary reconstruction is a successful procedure, failure is reported to occur in up to 13% of patients. In patients who complain of instability, revision surgery should be proposed and discussed with patients. The issue arising in this setting is the graft choice, being limited from the grafts used in primary surgery.
Methods: We retrospectively enrolled 38 consecutive patients who had undergone ACL one-stage revision with bone–patellar tendon–bone (BPTB) allografts from a single center with at least 2 years of follow up. The clinical evaluation was based on PROMs In addition, we recorded the rate of allograft re-rupture and post-surgical complications.
Results: Our series showed good PROMs at a minimum of 2 years follow up. Median IKDC, Lysholm, and Simple Knee Value were 82.8, 85.5, and 77.5, respectively. For the Tegner Activity Scale we recorded a median value of 8.0 before injury and 6.0 after surgery. Timing for return-to-play was between 6 and 9 months for 19 patients (54.3%). Regarding post-surgery complications, we recorded an overall rate of 15.79%, with however minor entity (Clavien–Dindo grade I). Allografts re-rupture rate was 10.5%.
Conclusion: BPTB allografts in one-stage ACL revision enabled patients to return to sports and to a good quality of life after the final follow up. Moreover, this type of graft has been shown to be a safe choice, being burdened by a low rate of post-surgical complications and re-rupture risk.

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1. Introduction

Rupture of the anterior cruciate ligament (ACL) of the knee is one of the most common injuries in young individuals involved in sports and the incidence is increasing in recent years [1,2]. In most cases, the indicated treatment is reconstruction surgery using autologous tendons as graft. Although primary ACL reconstruction (ACLR) is recognized as a successful procedure, failure is reported to occur in up to 13% of patients [3]. ACL failure can have a devastating effect, resulting in recurrent instability, possible pain for concurrent meniscal or chondral lesions and stiffness.

In patients who are still young and athletic and in all those who complain of symptoms of instability, revision surgery should be proposed and discussed with patients. The big challenge that arises for surgeons is the graft choice, it being limited by the previously used grafts in primary surgery.

To limit the morbidity of the harvest site and to avoid further weakening of the knee where autogenous tissue has already been harvested, many authors suggest allografts as suitable options for this purpose [4–6]. Non-irradiated allografts exhibit comparable infection risk and failure rate to autografts and are selected in 20–51% of revision ACLR [7,8]. This option is evidently not devoid of drawbacks, as concerns regarding infections, delayed remodeling and integration and immune rejection in addition to higher costs and difficulty in sourcing tissue must be considered [9,10]. However, there is a lack of studies in the literature detailing anatomical, biological and demographic data of donor graft.

The aim of the present study was therefore to evaluate outcomes after revision ACLR in a consecutive series of patients, regarding the type of allograft, considering the anatomical, biological and demographic data.

2. Materials & methods

2.1. Patients

This was a single-center retrospective cohort study where patients underwent ACLR with allograft between 2010 and 2021 performed by senior knee surgeons (M.B., M.P., M.T.) were screened for eligibility. Patients with two-stage revision surgery or primary allograft surgery for ACL, allografts different from bone–patellar tendon–bone (BPTB), follow up shorter than 2 years or incomplete medical or grafts records were excluded from the investigation.

Approval was obtained by the Ethical Committee board of the institution. Given the retrospective design of this study, the need for written informed consent of the included patients was waived, except for patients recalled for clinical testing with arthrometer KT-1000, who expressed their consent to data collection with respect to this procedure.

2.2. Data collection

Data collection was performed using a 48-question survey, designed to gather information on patient history and injury characteristics, return to sport (RTS), postoperative complications (according to the Clavien–Dindo classification of postoperative complications [11]) and new trauma, and functional scores following ACL revision with allograft. Functional scores were assessed using the International Knee Documentation Committee (IKDC) Questionnaire [12,13], the Lysholm Knee Score [14], the Simple Knee Value (SKV) [15], and the Tegner activity scale (TAS) [16]. The complete questionnaire is available in the Supplementary material.

To ensure clarity and maximize response reliability, the questionnaire primarily utilized multiple-choice questions, with open-ended questions included where detailed responses were necessary. Administered via e-mail in October 2022, the survey allowed patients to independently provide their responses, replying to the Principal Investigator if there was any doubt.

2.3. Clinical assessment

During October 2022 we convened the eligible patients for a follow up visit in the outpatient setting. Patients were tested in our Institution with the KT-1000 knee arthrometer. This arthrometer is a device that measures the anterior translation of the tibia while holding the femur in place. The results obtained provided an objective diagnosis of the status of the ACL in antero-posterior stabilization. Specifically, we evaluated the difference in millimeters of anterior tibial translation between the operated side and the healthy contralateral side taken as a control. A total of 12 patients were available for this clinical evaluation at the stipulated time.

2.4. Musculoskeletal tissue fact sheet

All allografts implanted were fresh frozen non-irradiated tissues, obtained from a single certified tissue bank (*ASST Gaetano Pini, Milan, Italy*). The procedure of tendons harvesting from the extensor apparatus from the bank consisted of several steps, all performed under sterile conditions in the same operating room. The tissue was packed in a double sterile plastic bag and contained in a sterile jar or in a triple sterile bag and non-sterile impermeable paper.

For transport, the tissue was packed in a polystyrene container with synthetic ice suitable for transport. If the material was not used immediately, it was removed from the packaging and stored at a temperature of –80 °C; if it was used within 24 h it was stored at a temperature between –20 °C and –80 °C.

At the time of use, the tissue was thawed through immersion in 0.9% saline solution at 37 °C fortified with Rifamycin (250 mg per 500 ml). Complete thawing was essential before use.

Each donor-derived musculoskeletal tissue had to be accompanied by a distribution information sheet on which was indicated information as follows: type of tissue, tissue and donor reference code, non-living beating-heart or still-heart donor retrieval, donor's age and gender, communicable diseases and social history, virological data for the following infections (HIV: Anti- HIV 1/2, HIV-RNA; HCV: Anti HCV, HCV-RNA; HBV: HbsAg, Anti-HBc IgM, Anti-HBs, HBV-DNA; LUE: TPHA), microbiological data for aerobes, anaerobes and fungi, storage data with the date of freezing, mode of storage and thawing, anatomical assessment of the tissue and its dimensions.

Each allograft was tested microbiologically for pathogens: 12 cases were positive for HbsAg, but negative for HBV-DNA, therefore suitable for donation [17].

Based on the above, the allografts were indicated as being suitable or not. Following the surgical procedure, the senior orthopedic surgeon completed the form containing information regarding the quality of the allograft and the entire documents were retransmitted to the tissue bank.

2.5. Surgical procedure

All surgical procedures were performed by senior knee surgeons with certified training in Sports Medicine (M.B., M.T., M. P.). Arthroscopic diagnostic evaluation was performed around all knees to assess whether concomitant lesions were present. Any chondral or meniscal lesion were treated before ACL surgery.

Routine removal of residual graft tissue and preparation of the notch were performed. Femoral and tibial hardware removal was performed to facilitate tunnel trajectory, in some cases with fluoroscopy assistance.

A 10-mm tibial bone tunnel was made with appropriate compasses settled between 50° and 55° medially to the anterior tibial apophysis. A transtibial femoral socket was performed using the Rigid Fix (Depuy, Mitek, USA) as a pointer to define the correct trajectory of the half tunnel. The depth of the femoral socket should be planned to be 5 mm greater than the length of the patellar bone block. Debridement of the sclerotic walls of the pre-existing tunnels was performed with a shaver.

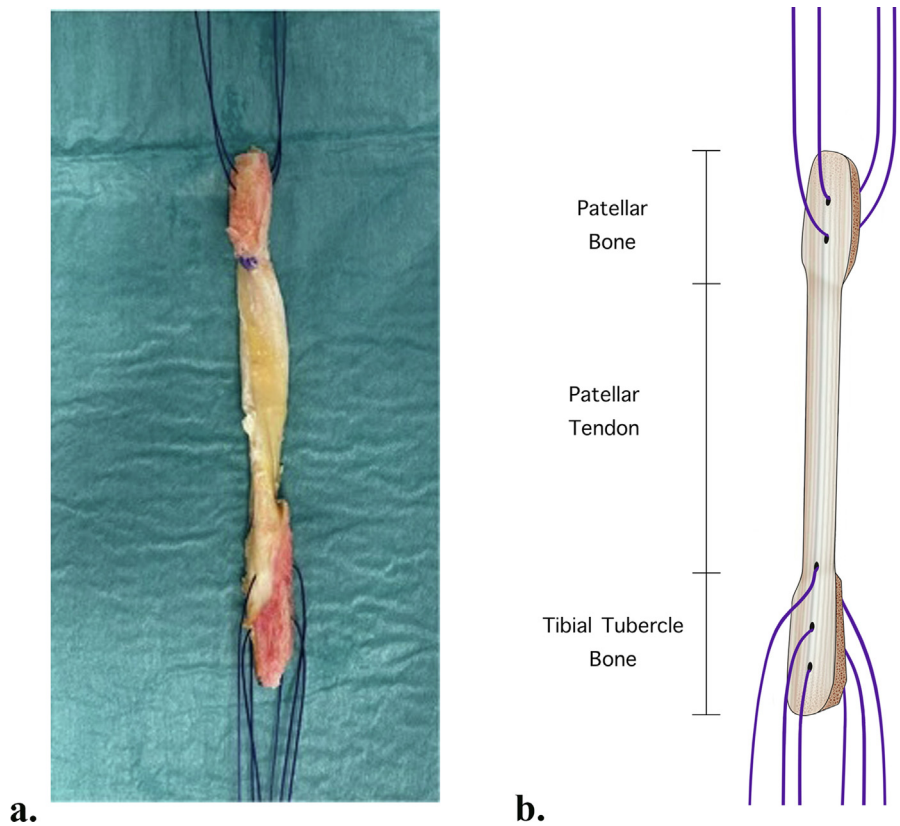

Figure 1. Bone–patellar tendon–bone allograft: intraoperative anteroposterior view (a) and corresponding schematic illustration (b).

The donor allograft was primarily soaked in sterile 0.9% saline solution at 37 °C fortified with Rifamycin (250 mg per 500 ml). This practice allowed defrosting of the part for further preparation (Figure 1(a), (b)).

The allograft was then placed through the tunnels with the patellar bract being fixed with two proximal resorbable pins using the Rigid-Fix system (DePuy Mitek, Raynham, MA, USA) and a bioabsorbable screw of a diameter congruent with tibial interference after adequate tension and verification of full range of motion in flexion–extension of the knee. In the immediate postoperative period, radiography was performed to verify the correct positioning of the tunnels and fixation hardware.

All patients underwent the same postoperative protocol: no weight bearing by using two crutches with hinged knee brace locked in full extension for 1 week, cryotherapy, non-steroidal anti-inflammatory drugs for 5 days (if not contraindicated), low-molecular-weight heparin until weight bearing was allowed.

From day 1 after surgery all patients were started on a continuous passive motion (CPM) machine for 3 h per day at minimal speed, with a range from 0 to 70°, and an increase of 10° every 2 weeks.

After 1 week weight bearing was allowed with a brace without range of motion restriction. At the same time, patients started kinesiotherapy and hydro-kinesiotherapy after stitch removal. The brace was removed after 3 weeks.

At 3 months, patients were allowed to run and begin sport-specific rehabilitation, with the goal of resuming pivoting activity at 6 months. RTS was allowed if specific criteria were met: isokinetic strength evaluation, limb symmetry index (LSI), H/Q ratio (hamstrings to quadriceps strength ratio) dynamic valgus control and single hop test were performed.

2.6. Statistical analysis

The characteristics of the study population were described by frequencies and percentages if the variables were categorical and by median and first (Q1) and third (Q3) quartiles if they were continuous. The distributions of the functional scores IKDC, SKV and Lysholm Knee Score and of the TAS evaluated before injury and after surgery were represented in boxplots. Patients and donors' characteristics related to subjects with and without rupture of the graft were compared through the exact Fisher test if variables were categorical or the *t*-test if they were continuous. Statistical analyses were performed with R 4.3.1 (https://www.R-project.org). All *P*-values were two-sided, with $P < 0.05$ considered to be statistically significant.

3. Results

The initial record of all patients who undrwent allograft ACL surgery was provided by the Regional Skeletal Muscle Tissue Bank and yielded 198 patients. Eighty-five patients were excluded for receiving allografts different from BPTB (Achilles' tendon, semitendinosus, gracilis, tibialis anterior), nine patients were excluded for incomplete data either of the medical history or of the graft, two patients were excluded because they did not reach the minimum follow up period of 2 years. Of these 102 patients, 27 did not provide complete answers to the questionnaires or were lost to follow up, while 37 were further excluded because they underwent primary reconstruction with allograft. A total of 38 consecutive patients matched the inclusion criteria and were therefore enrolled in the study (Figure 2).

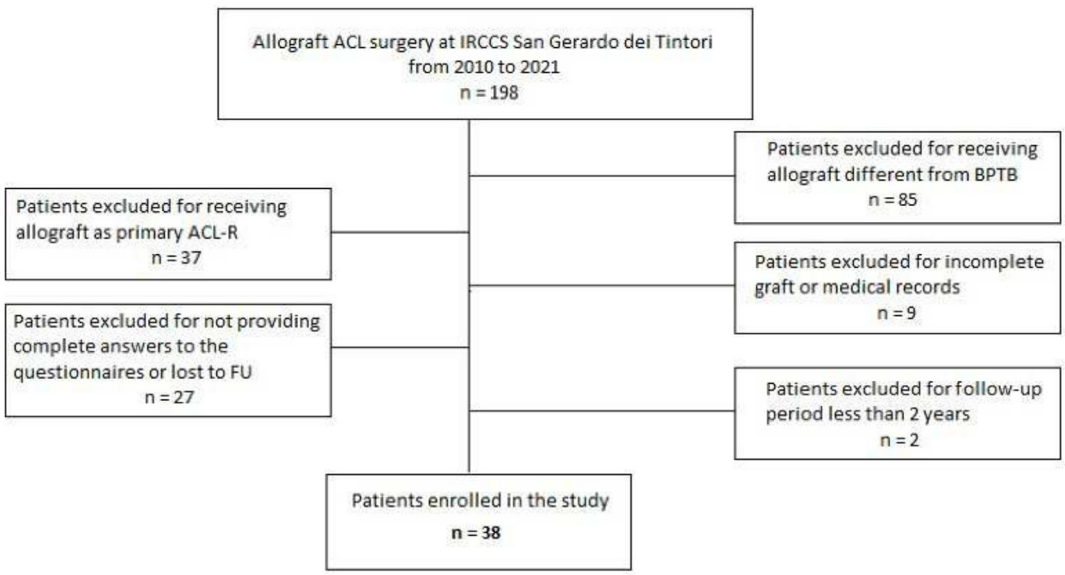

Figure 2. Patient enrollment flowchart. ACL, anterior cruciate ligament; ACL-R, ACL reconstruction; BPTB, bone–patellar tendon–bone; FU, follow up.

Table 1
Characteristics of the enrolled population and donors.

	Total (n = 38)
Patient characteristics	
Gender, n (%)	
Male	33 (86.8)
Female	5 (13.2)
Age at surgery (years), median (Q1–Q3)	26.1 (23.1–34.7)
Follow up time (years), median (Q1–Q3)	5.0 (4.1–6.8)
Weight (kg), median (Q1–Q3)	74.0 (70.0–81.8)
Height (cm), median (Q1–Q3)	179.5 (172.8–183.8)
BMI (kg/m^2), median (Q1–Q3)	23.5 (21.8–24.7)
First implant graft, n (%)	
BPTB	28 (73.7)
Semitendinosus + gracilis	3 (7.9)
Semitendinosus alone	6 (15.8)
LARS	1 (2.6)
First surgery, n (%)	
Isolated ACLR	29 (76.3)
ACLR combined with meniscectomy	7 (18.5)
ACLR combined with chondral shaving	1 (2.6)
ACLR combined with medial meniscus suture	1 (2.6)
Donor characteristics	
Gender, n (%)	
Male	31 (81.6)
Female	7 (18.4)
Age (years), median (Q1–Q3)	49.0 (40.3–52.0)
Age, n (%)	
≤50 years	23 (60.5)
>50 years	15 (39.5)
Retrieval setting, n (%)	
Non-living beating-heart	14 (36.8)
Still-heart	24 (63.2)

ACLR, anterior cruciate ligament reconstruction; BMI, body mass index; BPTB, bone–patellar tendon–bone; LARS, ligament augmentation and reconstruction system; Q1, first quartile; Q3, third quartile.

As described in Table 1 and 5 patients were females (13.2%) and 33 were males (86.8%), with a median age at surgery of 26.1 years (Q1–Q3 23.1–34.7). The median weight of the study population was 74.0 kg (Q1–Q3 70.0–81.8), the median height was 179.5 cm (Q1–Q3 172.8–183.8) and the median value of body mass index (BMI) was 23.5 (Q1–Q3 21.8–24.7). The median follow up time was 5.0 years (Q1–Q3 4.1–6.8), considering that it was decided to exclude patients who had a follow up time of less than 2 years.

The type of graft received as the first implant was then recorded, with the following results: 28 (73.7%) BPTB, three (7.9%) semitendinosus + gracilis, six (15.8%) semitendinosus alone and one (2.6%) Ligament Augmentation and Reconstruction System (LARS). The high number of patients who initially received a BPTB as their first graft can be explained by the fact that many patients came from our center, where, by choice of the senior surgeons, this graft appears to be the most widely used in the first implants.

Of the total number of primary reconstructions, 29 (76.3%) were isolated ACLR, in seven (18.5%) cases ACLR was combined with meniscectomy, in one case (2.6%) combined with chondral shaving, and lastly in another case (2.6%) combined with medial meniscus suture (Table 1).

The pattern of injury that led to the re-rupture of the ACL was also investigated and yielded the answers as follows: six sudden stops, three jump landings, one fall from above, 18 changes of direction, eight contacts with opponents, one accident, one mispositioning of foot support (Figure 3).

Considering the donor characteristics (Table 1), seven (18.4%) allografts were from females, while the remaining 31 (81.6%) were from males. The median age was 49.0 years (Q1–Q3 40.3–52.0), with 15 (39.5%) donors aged > 50 years. In 24 cases out 38 (63.2%) the explant was performed on a beating heart donor.

Table 2 details the characteristics of associated lesions in our study population: meniscal tears were observed in 25 patients (65.8%), with 13 (52.0%) involving the medial meniscus and 11 (44.0%) the lateral meniscus, and one (4.0%) being bilateral. Meniscectomy was the surgical procedure performed in 22 cases (88.0%).

Assessing the responses to the questionnaire, the knee function scores were examined after a minimum period of 2 years from surgery.

The distribution of the functional scores was displayed in boxplots (Figure 4). The median value of IKDC was 82.8 (Q1–Q3 75.3–88.2), that of SKV was 77.5 (Q1–Q3 65.0–85.0) and that of Lysholm Knee Score was 85.5 (Q1–Q3 80.0–91.0).

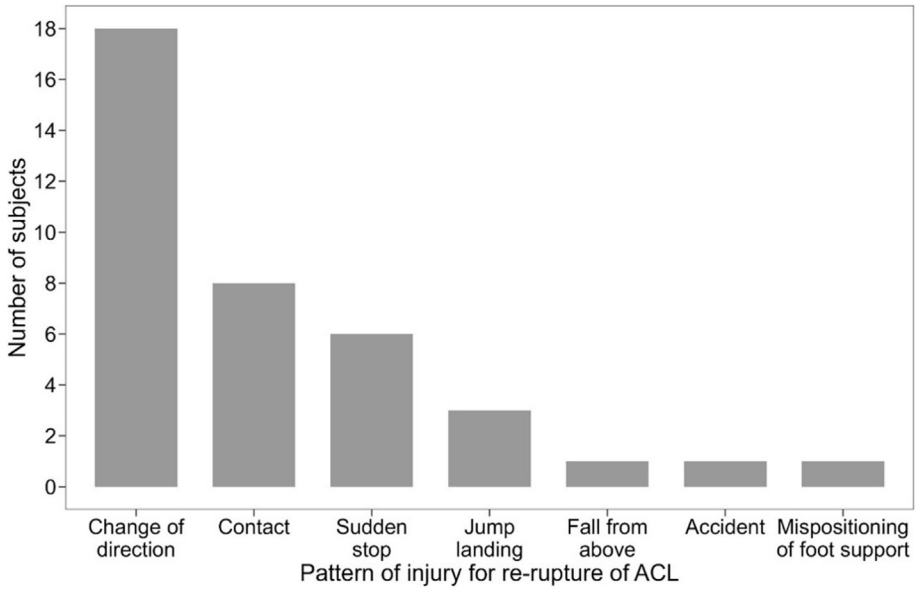

Figure 3. Distribution of the pattern of injury for the re-rupture of the anterior cruciate ligament (ACL).

Table 2
Characteristics of the associated lesions.

Patient characteristics	Total (n = 38)
Meniscal tears, n (%)	25 (65.8)
Medial meniscus	13 (52.0)
Lateral meniscus	11 (44.0)
Bilateral	1 (4.0)
Medial meniscus tears, n (%)	
Posterior horn	6 (42.9)
Body	3 (21.4)
Bucket handle	5 (35.7)
Lateral meniscus tears, n (%)	
Posterior horn	4 (33.3)
Body	1 (8.3)
Complex tear	5 (41.7)
Bucket handle	2 (16.7)
Surgical procedure, n (%)	
Meniscectomy	22 (88.0)

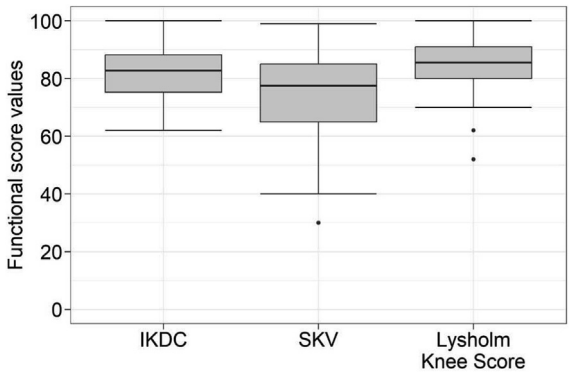

Figure 4. Boxplots of the distribution of the values of the functional scores International Knee Documentation Committee (IKDC), Simple Knee Value (SKV) and Lysholm Knee Score.

A total of 12 patients of the entire sample agreed to undergo outpatient examination and were tested with the KT-1000 arthrometer. The median difference of anterior tibial translation between the operated side and the healthy contralateral was 2.5 mm (Q1–Q3 1.0–4.0).

Of the 38 patients enrolled, two reported that they did not regularly participate in any sports before injury, while the other 36 reported having a reference sport activity (Table 3).

The most practiced sport in our population was soccer, with 24 participants (63.2%), followed by basketball with five participants, artistic gymnastics with two, while five participants practiced other sports (i.e., skiing, American football, Thai boxing, trekking and motorcycling).

Taking into account the number of training sessions per week, we gathered that of 36 participants performing regular training, 15 performed up to two sessions per week and 21 performed at least three.

The median value of the TAS was 8.0 (Q1–Q3 6.0–9.0) before injury and 6.0 (Q1–Q3 5.0–7.0) after surgery (Figure 5).

Of the 38 enrolled patients, three reported no sports activity post-surgery, whereas 22 (57.9%) resumed practicing the same pre-injury sport and 13 (34.2%) started a different sport (Table 4).

Of the 35 patients practicing sport after surgery, two patients who previously did not participate in any sports, began a regular practice. Twenty-two patients resumed the same sport, whereas 13 embarked on a different sport (Figure 6). These shifts in sports participation were reflected in the decrease in TAS value post-surgery, as shown above.

The timing for return-to-play (RTP) was between 6 and 9 months for 19 patients (54.3%), between 9 and 12 months for seven patients (20.0%) and over 12 months for nine patients (25.7%) (Table 4).

Six cases of postoperative complications (15.8%) were reported considering the 38 revision ACLRs with allografts. In the remaining 32 cases (84.2%), no postoperative issues were registered (Table 5). All six cases were classified as grade I according to Clavien–Dindo [11]. The complications were specifically as follows: two cases of chronic knee pain, one case of range of motion deficit, one case of neuropathy, one case of chondropathy, and one case of instability.

Fifteen patients (39.5%) reported new trauma after the surgery (Table 5); of these, nine were to the same operated knee, three to the contralateral knee, and three to both knees.

In traumas involving the operated knee, rupture of the neo-ligament occurred in four cases, corresponding to the 10.5% of the entire population (Table 6). Re-rupture was first assessed via clinical examination and afterwards confirmed through MRI scans.

Of the four patients with a re-rupture of ACL, one was female and three were males (Table 6), with a median age at surgery of 23.1 years (Q1–Q3 22.4–24.3), significantly different from age of subjects without re-ruptures (median 26.8 years,

Table 3
Characteristics of the sports practiced before injury.

	Total (n = 38)
Sport practiced before injury, n (%)	
No sport	2 (5.3)
Soccer	24 (63.2)
Basketball	5 (13.1)
Artistic gymnastics	2 (5.3)
Other	5 (13.1)
Training sessions per week, n (%) (n = 36)	
1–2 sessions	15 (41.7)
≥3 sessions	21 (58.3)

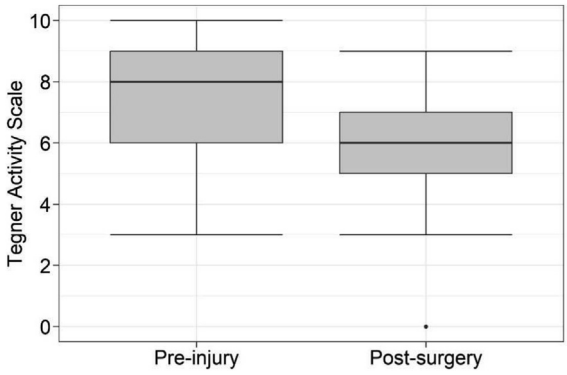

Figure 5. Boxplots of the distribution of the Tegner Activity Scale measured pre-injury and post-surgery.

Table 4
Characteristics of the sports practiced after surgery.

	Total (n = 38)
Sporting activity, n (%)	
No sports	3 (7.9)
Same pre-injury sport	22 (57.9)
Different pre-injury sport	13 (34.2)
RTP timing, n (%) (n = 35)	
6–9 months	19 (54.3)
9–12 months	7 (20.0)
≥12 months	9 (25.7)

RTP, return to play.

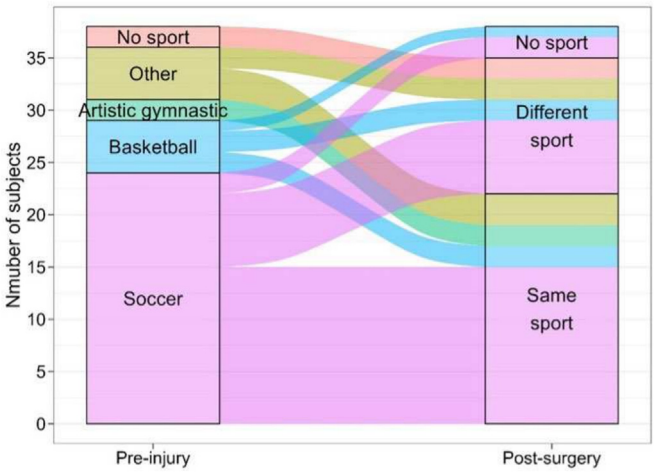

Figure 6. Characteristics of the sports practiced after surgery.

Table 5
Postoperative complications and traumas.

	Total (n = 38)
Postoperative complications, n (%)	
No complications	32 (84.2)
Complications	6 (15.8)
Trauma, n (%)	
No trauma	33 (60.5)
New trauma	15 (39.5)

Q1–Q3 23.3–35.5, P = 0.013). Median values of weight, height and BMI of patients experiencing a graft rupture were, respectively, 71.0 kg (Q1–Q3 66.8–76.0), 174.0 cm (Q1–Q3 166.5–179.3) and 23.8 (Q1–Q3 22.9–25.1). No statistically significant differences with the group of patients without re-ruptures were present.

Considering patients with a re-rupture, donors were one female and four males, with median age of 41.0 years (Q1–Q3 32.8–49.8). The age of the female donor was 32 years. All tissues were retrieved by still-heart donor and were successfully assessed by the surgeon at the time of surgery. No postoperative complications were detected in patients who experienced graft rupture.

4. Discussion

The present study aimed to investigate the efficacy and safety of using BPTB allograft in revision ACLR. The use of allografts is not limited to revisions alone but they are also used in primary reconstruction, with conflicting findings regarding the potential benefits and risks: in a recent study encompassing over 16,000 ACLRs from a community registry in the USA, allografts were employed in 42.4% of primary reconstruction and 78.8% of revisions, showing no significant difference in outcomes [18].

Table 6
Patient and donor characteristics related to subjects with and without rupture of the graft.

	Re-rupture (n = 4)	No re-rupture (n = 34)	P
Patient characteristics			
Gender, n (%)			0.446
Male	3 (75.0)	30 (88.2)	
Female	1 (25.0)	4 (11.8)	
Age at surgery (years), median (Q1–Q3)	23.1 (22.4–24.3)	26.8 (23.3–35.5)	0.013
Weight (kg), median (Q1–Q3)	71.0 (66.8–76.0)	75.5 (70.0–81.8)	0.493
Height (cm), median (Q1–Q3)	174.0 (166.5–179.3)	180.0 (175.0–184.8)	0.301
BMI (kg/m^2), median (Q1–Q3)	23.8 (22.9–25.1)	23.5 (21.8–24.7)	0.781
Time from injury to surgery (months), median (Q1–Q3)	12.0 (7.4–19.4)	12.8 (6.6–21.8)	0.876
Meniscal tears, n (%)	2 (50.0)	23 (67.6)	0.595
Medial meniscus	2 (100.0)	11 (47.8)	
Lateral meniscus	0	11 (47.8)	
Bilateral	0	1 (4.3)	
Donor characteristics			
Gender, n (%)			0.651
Male	3 (75.0)	28 (82.4)	
Female	1 (25.0)	6 (17.6)	
Age (years), median (Q1–Q3)	41.0 (32.8–49.8)	49.0 (41.0–52.8)	0.530

BMI, body mass index; Q1, first quartile; Q3, third quartile.

First, we considered it appropriate to opt for the use of an allograft to avoid the further weakening of another harvest site in the patient, because it was revision surgery. Opting for a second autograft inevitably involves further sacrifice of structures from the same knee or even from the contralateral knee in a patient who had already undergone a first harvest.

Regarding the choice of the specific type of allograft, it was dictated not only by the confidence of individual surgeons but also by important properties of this graft. BPTB in fact, more than other grafts, enables larger diameters to be easily obtained, often required in revision surgeries to perform one-stage ACLR using the same tunnels. One-stage revision ACLR is assumed precisely to avoid the intermediate step of bone-grafting the old tunnels, with the obvious advantage of avoiding an additional surgical procedure. Moreover, from a purely anatomical point of view, the patellar tendon is a true ligament in that it connects bone (patella) to bone (tibial tubercle) [19].

Although in the literature there are studies on the results of individual autograft types chosen, there is a lack of evidence, regarding allografts. The present study represents, to the best of our knowledge, one of the largest single-center series of ACL one-stage revision surgeries using BPTB allografts and offers some points to discuss.

All patients enrolled underwent one-stage revision. This procedure is viable only when there is no-widening of old tunnels (under 15 mm), when old tunnels can be bypassed or partially overlapped, when previous hardware is easily removable, when good bone stock is present, and the range of motion is complete [6]. Conversely, two-stage revision is performed in only 8% to 9% of revision ACLRs, after a 3- to 6-month interval [20].

The resistance and stiffness may vary among different allografts, although most exceed the tensile strength of the native ACL. BPTB grafts can provide larger diameters, correcting misplacement of previous tunnels, and addressing potential substance loss by allo- or auto- (from iliac crest or tibia) bone graft applied at both ends, even in a one-stage procedure.

To begin, the population enrolled in the present study shows a clear prevalence of the male sex (n = 33), with 86.8% of the total. This is consistent with a recent metanalysis, in which male sex appears to be a risk factor for re-rupture and revision [21]. This can be ascribed to the higher participation in pivoting sports and high-energy activities of males rather than females. Moreover, in almost one in four cases (23.68%) the primary reconstruction included associated lesions, mostly meniscal, an additional recognized risk factor for ACL failures.

The injury pattern was also typical, with 78.95% of cases (30 of 38) reporting non-contact trauma. Our sample's median age was 26.1 years (Q1–Q3 23.1–34.7): several articles demonstrated that younger athletes returning to high-level sports after ACLR are at risk of graft rupture or contralateral ACL injury, in particular soccer players and skiers [22]. In particular, patients under 20 years old have a higher risk of revision ACLR than those over 20 years and altogether revision ACLR is performed in a younger age group compared with primary ACLR [23]. In the literature, risk factors associated with graft revision identified by the ACLR registry include age, race, BMI, graft type: our patients reported a median weight of 74.0 kg (Q1–Q3 70.0–81.8 kg), and a median height of 179.5 cm (Q1–Q3 172.8–183.8 cm). For BMI we recorded a median value of 23.5 (Q1–Q3 21.8–24.7).

The type of graft received as first implant was in most cases BPTB autograft. This is not to be intended as an augmented failure rate of this autograft, but it comes from the fact that many patients had undergone the first ACLR at our institution, where BPTB autograft is the first choice.

Regarding functional scores, investigated through patient-reported outcome measures (PROMs), we recorded a median value of 82.0 (Q1–Q3 75.3–88.2) for IKDC Questionnaire, 77.5 (Q1–Q3 65.0–85.0) for SKV and 85.5 (Q1–Q3 80.0–91.0) for Lysholm Knee Score at a median follow up period of 5.0 years (minimum 2.0 years). Patients who underwent ACL revisions reached good scores in all the three scales, indicating that our sample was satisfied with their performance, experiencing fewer symptoms and disability, indicative of successful surgery.

Analysis by Johnson et al. showed a median IKDC score of 73.8 after revision ACLR with BPTB allograft after a follow up of 52 months [24] and Smith et al. reported a median IKDC of 71 and a Lysholm of 75 [25].

A review by Wright et al. showed that IKDC scores in the revision group were comparable to those observed in primary settings [8].

In addition to subjective reported evaluation, patients were tested using the KT-1000 knee arthrometer not earlier than 2 years after surgery. When comparing the operated and the contralateral knee, no patients out of the 12 who underwent the test had a side-to-side difference greater than 4 mm, the cut-off for a new ACL rupture [26]. Therefore, this objective parameter confirms that which has been previously mentioned regarding PROMs, although being based only on a few patients. It is vital to highlight that this objective test was based on a very small sample, with a selection bias coming from the fact that patients who consent for testing were from a ‘‘successful” subgroup.

Regarding physical activity, we assessed the level of RTS through TAS both pre-injury and post-surgery. RTS is a crucial outcome as it helps evaluate the success of the surgery in an active population. Almost all patients (n = 36, 94.7%) reported practicing sports before ACL rupture and the majority participated in competitive level events: median TAS pre-injury of 8.0. Sports involving pivoting (e.g., football, basketball, skiing) were the most common in our sample: athletes engaged in such sports are at higher risk of sustaining ACL injury during their careers [27]. Our findings indicate that after ACL revision with BPTB allografts, most patients continued to engage in intense sporting activities (n = 35, 92.1%). Regardless of the type of graft, Legnani et al. reported a 76% rate of RTS after revision ACLR [28]. Although a few patients stopped participating in sports, others who were previously non-athletic changed their lifestyle to include sports activities: more than half (n = 22, 57.9%) resumed the same sports activity as before, while a significant portion opted for a change (n = 13, 34.2%). The RTS occurred within a range of 6 to 9 months for most patients (n = 19, 54.3%), with only 25.7% experiencing a return after more than 12 months. In accordance with the literature, patients generally resume sporting activities between 6 and 12 months postoperatively (9.8 months), a timeframe influenced by factors such as the nature of the sport and psychological and physical aspects [29]. A TAS pre-injury of 8 (Q1–Q3 6.0–9.0) suggests that our sample was based on high-level athletes having previously experienced a primary ACL rupture and reconstruction. Patients were encouraged to engage in physical activities both for surgery preparation and to resume normal daily and athletic activities. When comparing with TAS post-surgery, sports activity level was lower, with a median score of 6.0. This finding appears consistent with the literature: Johnson et al. reported a statistically significant difference between pre-injury, post-primary ACLR and post-revision ACLR, respectively, with a score of 9, 7 and 6 [24]. Lind et al. congruently suggest that functional activity, based on TAS, was lower 1 year after revision compared with primary ACLR [30]. Studies reported an RTS to their pre-injury level of 56–74% after revision: athletes attribute the ACL injury as the primary reason for the reduced level of sports activity, for both athletic and psychological components [31].

Recent systematic reviews have shown that non-irradiated allografts yield comparable results to autografts in terms of patient satisfaction, knee functional scores, and clinical failure rates. However, they are still believed to carry a higher risk of graft rupture, especially in young and active patients [8,27].

In our study, only fresh-frozen non-irradiated grafts were utilized, maintained at an appropriate temperature of −80 °C until their use: non-irradiated allografts are valid options with a high potential for satisfactory results, because radiations are noted for modifying collagen fibers and extracellular matrix reducing strength and resistance of grafts [32,33]. Slowly defrosting in sterile physiological solution at 37 °C and antibiotics pre-soaking (Rifamycin 250 mg per 500 ml), reduce the risk of infection in the operating room: as is evident in the complications, none exhibited graft rejection or post-transplant infection. Furthermore, none of the analyzed tissue or donor characteristics showed an increased risk of graft rupture. In literature, there are no report of immune-mediate response using allograft [33] and a postoperative infection rate of 0.6–0.8%, not higher compared to autograft, in revision setting: in primary ACLR, a lower 0.3% infection risk was observed [18,34,35]. All of the postoperative complications recorded in our series were classified as grade I according to Clavien–Dindo, and were therefore to be regarded as trivial. The predominant complications noted in our sample (loss of range of motion and chronic knee pain), are consistent with findings reported in the literature [36]. Revision ACLRs do have not higher complication rates than primary just as allograft compared to autograft [36,37]: according to these findings, the use of allografts for ACL revision appears to be a safe strategy, devoid of increased risks for early and delayed postoperative complications [6].

Patients in our series sustained a 10.53% reinjury rate (n = 4). In a recent systematic review, overall failure rate of revision ACLR is reported to range up to 25% [38], testifying that this is intended to be a complex clinical setting. Restricting the focus in the literature to only ACL revisions using patellar tendon allografts, the re-rupture rates are highly variable, ranging from 3.77% to a peak of 28% [24,25,39]. A recent *meta*-analysis on revision ACLR outcomes found instead no overall difference between autograft (4.1%) and allograft (3.6%) [40]. The failure rate observed in our cohort may be attributed to several factors, including the young age, the male gender, concomitant lesions, and a high level of TAS as mentioned above. In our statistical analysis, a correlation was found (P = 0.013) between age and revision failure, whereas no correlation was found with meniscal tears (P = 0.595). Therefore, patients who experienced allograft failure were significantly younger.

A limitation of the present study was that no lateral extra-articular tenodesis or anterolateral ligament reconstruction was performed. In recent years, in fact, it has been shown how these additional procedures can improve ACLR outcomes, especially in the revision setting. In the population of this study, we can speculate that these could have improved outcomes. An additional limitation of our study was the loss of several patients during follow up, which could introduce selection bias: to mitigate this, we applied strict inclusion criteria and required a minimum follow up of 2 years.

The issue of cost and sourcing of this type of graft certainly deserves consideration. The cost is higher than the use of autologous grafts and sourcing is not always smooth, but in our opinion these limitations are not absolute, but worth considering in the cost–benefit balance.

The literature suggests considering these additional surgeries above all in revisions, young patients and pivoting sports, features detectable in our sample [41,42].

Overall, the clinical and functional mid-term results of ACL revision in our series are good and this appears to be the most important finding of our study, testifying how BPTB allograft can be a useful tool in the revision armamentarium of modern knee surgeons.

5. Conclusions

The use of BPTB allografts for ACL one-stage revision surgery appears a safe and effective option, yielding good mid-term results in function and RTS. BPTB allografts should be taken into consideration above all in patients with a history of multiple revisions, in order not to further harm the knee for the harvest. Younger patients who compete in pivoting sports should be assumed to be at even higher risk of re-rupture and therefore lateral extra-articular tenodesis or anterolateral ligament reconstruction are procedures to be considered. Modern knee surgeons should have this option in their surgical armamentarium.

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Ethics

The study was conducted in accordance with the Declaration of Helsinki and approved by the Ethics Committee of Fondazione IRCCS San Gerardo dei Tintori.

CRediT authorship contribution statement

Marco Turati: Writing – review & editing, Resources, Project administration, Methodology, Investigation, Conceptualization. **Filippo Maria Anghilieri:** Writing – original draft, Visualization, Investigation, Formal analysis. **Marco Crippa:** Writing – original draft, Methodology, Investigation, Formal analysis. **Massimiliano Piatti:** Resources, Investigation, Conceptualization. **Luca Rigamonti:** Writing – review & editing, Resources, Methodology, Investigation, Conceptualization. **Elena Tassistro:** Visualization, Methodology, Formal analysis. **Sabrina Trapletti:** Writing – original draft, Investigation, Formal analysis. **Marco Bigoni:** Supervision, Resources, Project administration, Methodology, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.knee.2025.05.034.

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