

Original Article

Comparison of free fibular flap versus iliac crest bone graft reconstruction for traumatic segmental forearm bone defects: a retrospective matched cohort study focusing on efficacy and donor-site complications

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Abstract: Objective: To compare the efficacy and donor-site complications of free fibular flap (FFF) and iliac crest bone graft (ICBG) in the reconstruction of traumatic segmental forearm bone defects. Methods: This retrospective matched cohort study included 120 patients (60 treated with FFF, 60 treated with ICBG) between January 2019 and June 2025. Propensity score matching (1:1) was performed to balance baseline characteristics between groups. The primary outcomes included bone union time, bone resorption rate, nonunion rate, re-fracture rate, and secondary surgery rate. Secondary outcomes included upper limb function at 12 months (assessed using the Disabilities of the Arm, Shoulder and Hand [DASH] score, grip strength ratio, wrist range of motion, forearm rotation) and donor-site complications (e.g., chronic pain, gait abnormality, sensory disturbance, donor-site weakness, hernia/abdominal bulging, and wound complication). Results: Compared with FFF, ICBG was associated with a significantly shorter union time (5.00 ± 0.86 vs. 6.51 ± 1.30 months, $P < 0.001$) but a significantly higher bone resorption rate ($13.80 \pm 3.65\%$ vs. $7.04 \pm 2.00\%$, $P < 0.001$). Nonunion rate (10.0% vs. 13.3% , $P = 0.776$), re-fracture rate (both 5.0% , $P = 1.000$), and secondary surgery rate (13.3% vs. 18.3% , $P = 0.617$) were comparable between the two groups. Regarding functional outcomes, FFF was associated with a significantly higher grip strength ratio (0.82 ± 0.08 vs. 0.76 ± 0.09 , $P < 0.001$) and greater forearm rotation ($132.12 \pm 14.91^\circ$ vs. $120.27 \pm 18.53^\circ$, $P = 0.001$), whereas DASH scores and wrist range of motion were comparable between groups. In terms of donor-site complications, FFF was associated with significantly higher rates of gait abnormality (16.7% vs. 1.7% , $P = 0.011$) and donor-site weakness (20.0% vs. 3.3% , $P = 0.010$). ICBG showed a borderline higher rate of chronic pain (15.0% vs. 3.3% , $P = 0.058$) and hernia/abdominal bulging occurred only in the ICBG group (5.0% vs. 0). Multivariable regression demonstrated that ICBG was independently associated with a reduced risk of gait abnormality (OR = 0.103, 95% CI: 0.012-0.923, $P = 0.042$). Subgroup analysis of patients with defect length ≥ 6 cm further highlighted these differences. Conclusions: Both FFF and ICBG are effective for traumatic segmental forearm bone defects; however, they demonstrate distinct advantages and donor-site morbidity profiles. ICBG provides faster union but is associated with higher bone resorption and a potential increase in chronic donor-site pain. In contrast, FFF offers superior functional recovery but carries a higher risk of lower-extremity donor-site complications. Clinical decisions should be individualized based on defect length, functional demands, and patients tolerance to specific donor-site complications.

Keywords: Forearm bone defect, free fibular flap, iliac crest bone graft, donor-site complication, retrospective matched cohort study

Introduction

Post-traumatic segmental bone defects of the forearm are among the most challenging clinical problems in hand surgery and reconstructive surgery. High-energy injuries, including machine crush injuries, traffic accidents, falls

from height, and blast injuries, often result in extensive bone loss accompanied by severe soft tissue injuries, vascular and nerve contusions, and wound contamination, making primary bone grafting almost impossible. Following thorough debridement and temporary stabilization, bone defects encountered during second-

ary reconstruction often exceed 4 cm or 1.5 times the diameter of the affected diaphysis [1, 2]. For such defects, traditional non-vascularized autologous cancellous bone grafting is limited by insufficient central vascularization and slow creeping substitution. Consequently, non-union rates at 6 months after surgery may reach 30%-50%, and the transplanted bone is prone to resorption, leading to fixation failure, re-fracture, and loss of limb length [3-5]. Therefore, vascularized free bone flap transplantation has become a “gold standard” for managing long-bone defects requiring biological reconstruction [6].

Currently, the management of traumatic segmental forearm bone defects requires individualized decision-making based on defect size, soft tissue conditions, and infection status. For defects smaller than 4 cm with good soft tissue coverage, non-vascularized autologous bone grafting remains a viable option. However, for defects larger than 4 cm, the reliance on creeping substitution may result in insufficient osteogenesis, increased bone resorption, and a higher risk of nonunion, limiting its ability to restore mechanical stability [4, 5]. The Masquelet induced membrane technique offers an effective approach for infected or complex bone defects; however, it requires two-stage surgery, prolongs treatment period to approximately 5-6 months, and is associated with a complication rate of up to 21% [7, 8]. Ilizarov bone transport is another established reconstructive method but is less favorable for forearm defects due to prolonged external fixation, which seriously affects patient quality of life. Therefore, for defects ≥ 6 cm or those combined with extensive soft tissue injury, vascularized free bone flap reconstruction has become an increasingly preferred option [6].

Among these options, free fibular flap (FFF) and the iliac bone flap (ICBG) represents two commonly used autologous bone reconstruction strategies. FFF provides long segment of vascularized cortical bone (up to approximately 25 cm), offering excellent mechanical stability, which facilitates early functional rehabilitation. However, donor-site morbidity remains a concern, including ankle joint instability and gait disturbance, with reported complication rates ranging from 10% to 30% [9]. In contrast, ICBG contains abundant cancellous bone and bone

marrow-derived mesenchymal stem cells, providing strong osteogenic potential and facilitating faster healing. Nevertheless, ICBG is associated with greater long-term graft resorption, chronic donor-site pain (10%-20%), and abdominal wall complications, including bulging or hernia [10-12]. Although both bone flaps have good clinical reports, direct comparative studies evaluating their efficacy and donor-site complications in segmental forearm bone defects remain scarce. Existing evidence is largely derived from small-sample retrospective studies, without adequate adjustment for baseline differences, resulting in limited evidence to guide clinical decision-making [13, 14].

The fibula is the longest tubular cortical bone in the human body, with its vascular supply primarily derived from the peroneal artery and accompanying veins. Its relatively constant anatomy and long vascular pedicle (up to 8-10 cm) make it suitable for microvascular anastomosis to recipient vessels such as the radial or ulnar arteries during forearm reconstruction [15]. A vascularized fibular flap can provide up to 25 cm of cortical bone, sufficient to repair extensive segmental defects involving the ulna or radius, and may be harvested as an osteocutaneous flap to simultaneously address associated soft tissue defects. Due to its thick cortical structure and excellent resistance to torsional and shear forces, FFF can provide early mechanical stability after internal fixation and facilitate functional rehabilitation [9]. Previous studies have reported bone union rates of 85%-95% after FFF reconstruction of forearm bone defect but with a relatively prolonged union time (approximately 6-8 months), likely because cortical bone remodeling and incorporation occur more slowly than that of cancellous bone [16]. Nevertheless, FFF-associated donor-site complications cannot be ignored. Fibular harvest may result in ankle instability, gait abnormalities (especially during walking on slopes or uneven ground), weakness of great toe extension, and sensory disturbances within the distribution of the superficial peroneal nerve. The overall incidence of donor-site complications has been reported to range from 10%-30% [17].

The iliac bone is a tricortical bone graft rich in cancellous bone and bone marrow-derived

mesenchymal stem cells, providing substantial osteogenic potential. Its vascular supply comes from the deep circumflex iliac artery, with a vascular pedicle length of approximately 6-8 cm, which facilitates microvascular anastomosis during reconstruction [18, 19]. The advantage of ICBG lies in excellent osteogenic capacity, as cancellous bone promotes early revascularization and remodeling. Clinically, ICBG achieves bone healing approximately 1-2 months earlier than FFF, with an average healing time of 4-6 months [10]. However, the long-term bone resorption rate of ICBG is significantly higher than that of FFF, especially in the forearm that bears shear stress. Progressive bone resorption can lead to fixation loosening, mechanical axis alteration, and even re-fracture [11]. In terms of donor-site morbidity, ICBG harvesting has been associated with chronic pain in approximately 10%-20% of patients and may cause complications such as abdominal wall bulging or hernia, especially when extensive graft harvesting is performed near the anterior superior iliac spine. In addition, injury to the lateral femoral cutaneous nerve may lead to anterolateral thigh sensory disturbances [12-14].

Although both of FFF and ICBG have demonstrated good clinical outcomes, studies directly comparing their efficacy and safety in the reconstruction of forearm bone defects remain limited. Most available studies are retrospective case analyses of a single bone flap, with significant differences in inclusion criteria, defect length, follow-up time, and outcome indicators among different studies, making it impossible to conduct reliable indirect comparisons. To date, only a small number of comparative studies involving forearm bone defects have been reported, most with limited sample sizes (<30 patients per group), without propensity adjustment or systematic assessment of the long-term impact of donor-site complications on patient quality of life [20, 21]. Moreover, previous assessment of upper limb functional outcomes often focused solely on joint range of motion, lacking comprehensive considerations of grip strength, fine motor skills, and patient-reported outcome measures such as the Disabilities of the Arm, Shoulder and Hand (DASH) scales. In terms of donor site complications, most studies only reported pain or sensory abnormalities, with insufficient

quantification of gait abnormalities, donor site weakness, and abdominal wall hernias, resulting in a lack of comprehensive evidence to guide individualized decision-making.

Therefore, the selection of an optimal grafting strategy for traumatic segmental forearm bone defects remains clinically challenging. ICBG provides rapid bone healing but is associated with a higher risk of long-term graft resorption and chronic donor-site pain, whereas FFF offers good mechanical strength and potential functional advantages but carries the risk of lower - extremity donor-site morbidity. For young patients with high physical demands or those requiring reconstruction of large defects (≥ 6 cm), determining which bone graft remains an important clinical consideration. Similarly, in elderly patients or those with factors associated with increased donor-site morbidity, such as poor abdominal wall integrity and low body mass index, the potential benefits of ICBG or FFF must be carefully weighed against procedure-related complications.

Based on this background, this study adopted a retrospective matched cohort study design to compare the clinical outcomes and donor-site complications of FFF and ICBG for the reconstruction of traumatic segmental forearm bone defects.

Materials and methods

Research design

This was a single-center, retrospective matched cohort study. The study protocol was reviewed and approved by the Ethics Committee of the 960th Hospital of the PLA. Due to the retrospective nature of the study, the requirement for informed consent was waived. All procedures were conducted in compliance with the principles of the Declaration of Helsinki (2013).

Study subjects

This study included patients who underwent FFF or ICBG reconstruction for traumatic segmental bone defects of the forearm at the 960th Hospital of the PLA between January 2019 and June 2025.

Inclusion criteria: (1) Age between 18 and 70 years; (2) Unilateral segmental bone defects

involving the radius, ulna, or both, with a length ≥ 4 cm or exceeding twice the diameter of the affected diaphysis; (3) Reconstruction using either a FFF or a ICBG approach, performed as either a single-stage or staged procedure; (4) Postoperative follow-up time ≥ 12 months; (5) Availability of complete clinical records, radiographic evaluations, and functional assessment data.

Exclusion criteria: (1) Pathological fractures, active infections (Cierny-Mader type 3/4), or uncontrolled osteomyelitis; (2) Severe ipsilateral lower-extremity vascular or neurological injuries precluding fibular harvest, or pelvic fractures/severe osteoporosis preventing iliac crest harvesting; (3) Forearm amputation or failed limb salvage; (4) Loss to follow-up or missing key data exceeding 20%.

Data collection and variable definition

Demographic and clinical data were collected from the electronic medical record system, Picture Archiving and Communication System (PACS), and follow-up records from the rehabilitation department.

Baseline characteristics

Baseline demographic and clinical characteristics included age, sex, body mass index (BMI), smoking history, diabetes mellitus, hypertension, injury mechanism (car accident/machine crush injury/fall from height/blast injury), Gustilo classification (I-III B/C), location of bone defect (radius/ulna/double bone), defect length (measured using postoperative X-ray), associated injuries (blood vessels/nerve/tendons), interval from injury to bone reconstruction (days), and number of previous surgical procedures.

The defect length was measured based on postoperative radiographs. Associated injuries were recorded according to the initial clinical evaluation and operative findings.

Surgical and perioperative variables

Surgical and perioperative data included total surgical time (min), postoperative hospital stays (days), and duration of donor-site drainage tube retention (days).

Observation outcomes

Primary outcomes

Bone union time was defined as the interval from reconstruction surgery to radiographic confirmation of bone healing. Radiographic union was considered achieved when three consecutive anteroposterior and lateral radiographs demonstrated bridging bone formation or cortical continuity across at least three cortices, without evidence of internal fixation loosening or failure. Radiographic evaluations were performed at 1, 3, 6, 9, 12, and 18 months after surgery.

Bone resorption rate: resorption rate was defined as the percentage reduction in reconstructed bone flap length at the last follow-up compared with the immediate postoperative measurement.

Nonunion: Nonunion was defined as the absence of progressive radiographic healing at 9 months after surgery, or the requirement of a revision surgery.

Refracture: Refracture was defined as new fracture that occurred at the reconstructed anatomical site, as confirmed by X-ray.

Secondary surgery rate: Secondary surgery was defined as any additional surgical intervention required due to nonunion, infection, internal fixation failure, or malunion after the initial reconstruction procedure.

Secondary outcomes

Upper limb functional outcomes: Upper limb function: Upper limb function was evaluated at 12 months after surgery by a rehabilitation physician who was blinded to treatment allocation. All range-of-motion measurements were performed using a standard goniometer with in a standardized seated position. Each measurement was repeated three times, with the mean value recorded.

DASH score: The Chinese version of the DASH questionnaire was completed independently by each patient. The DASH score ranges from 0 to 100, with higher scores indicating greater disability. The score was calculated as [(sum of

completed responses)/number of completed responses - 1] × 25.

Grip strength ratio: Grip strength was measured using a Jamar dynamometer (second handle position). Patients were assessed in a seated position with the shoulder adducted, elbow flexed at 90°, forearm in neutral rotation, and wrist in a neutral position. The grip strength ratio was calculated as: mean grip strength of affected side/mean grip strength of contralateral side.

Wrist range of motion: Active palmar flexion and dorsiflexion were measured with the forearm stabilized on a table and the elbow flexed at 90°. Total wrist motion arc = flexion + extension.

Forearm rotation: Active forearm pronation and supination were measured with the elbow flexed at 90° and positioned close to the trunk. Total rotation arc = pronation + supination.

Donor site complications: Chronic pain: Chronic donor-site pain was defined as persistent pain lasting for ≥3 months, with a visual analogue scale (VAS) score ≥3/10.

Gait abnormality: Gait abnormality was defined as patient-reported or clinically detected abnormal walking patterns, including difficulty walking on slopes or uneven ground, or subjective lower-extremity instability.

Sensory disturbances: In the FFF group, sensory disturbance was defined as numbness involving the lateral lower leg or dorsum of the foot; In the ICBG group, sensory disturbance was defined as numbness within the sensory distribution of the lateral femoral cutaneous nerve following iliac crest harvesting.

Donor-site weakness: In the FFF group, donor-site weakness was defined as inability to perform single-leg heel raising or clinically evident weakness involving ankle or toe flexion; in the ICBG group, donor-site weakness was defined as clinically detectable abdominal wall protrusion or hernia confirmed by ultrasound.

Wound complications: Wound complications included donor-site dehiscence, infection, and delayed wound healing.

Propensity score matching

PSM was performed using the MatchIt package in R software to minimize baseline differences between the FFF and ICBG groups. The propensity score model included the following covariates: age, sex, defect length, defect location, Gustilo classification, smoking history, and diabetes mellitus. The nearest-neighbor (1:1) matching without replacement was performed using a caliper width of 0.2 standard deviations of the logit of the propensity score. The balance of baseline characteristics between groups was assessed using standardized mean differences (SMDs), with an SMD <0.1 indicating adequate covariate balance. When residual imbalance remained after PSM, additional sensitivity adjustment was performed according to clinically relevant variables (age within ±5 years and defect length within ±1 cm), while exact matching was maintained for categorical variables. The matching process is illustrated in **Figure 1**.

Statistical analysis

Statistical analysis was performed using SPSS 26.0 (IBM Corp., Armonk, NY, USA) and R 4.2. Normality of continuous variables was assessed using the Shapiro-Wilk test.

Continuous variables with normal distribution were expressed as mean ± standard deviation (SD), and between-group comparisons were conducted using the independent sample t-test. Welch's t-test correction was applied when variance homogeneity was not satisfied. Non-normally distributed continuous variables were expressed as median (interquartile range, IQR) and compared between groups using the Mann-Whitney U test. Categorical variables were expressed as frequency (percentage), and compared between groups using the chi-square test or Fisher's exact test, as appropriate. Bone union time was analyzed using Kaplan-Meier method, and differences between groups were assessed using the log-rank test. Multivariate linear regression analyses were conducted with bone union time as the dependent variable, and the following covariates were included: graft type (FFF vs. ICBG), age, smoking, defect length, Gustilo classification (III/IV vs. I/II). Binary Logistic

FFF vs. ICBG for forearm bone defects

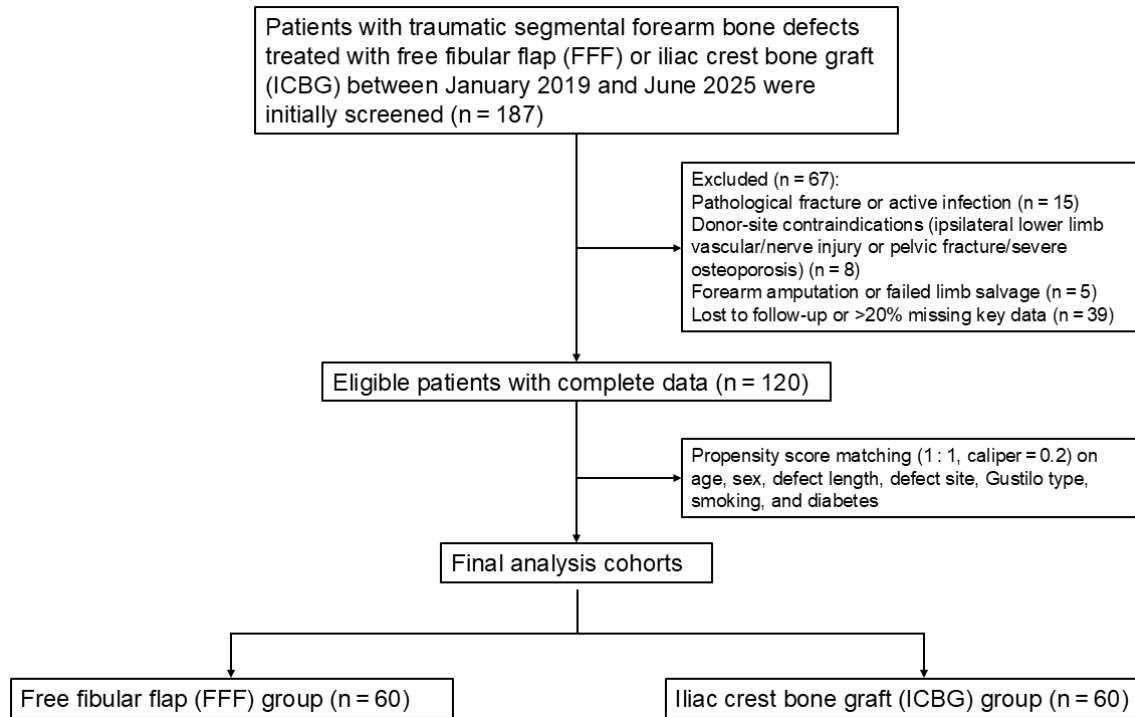


Figure 1. Flow diagram of patient screening, matching, and group assignment. Notes: FFF, free fibular flap; ICBG, iliac crest bone graft.

regression analyses were performed to evaluate factors associated with donor-site complications, including chronic pain and gait abnormality, with adjustment for age, smoking history, and defect length. Since there were no abdominal wall hernia/bulging events in the FFF group, multivariable regression analysis was not performed for this outcome. All statistical tests were two-sided, and $P < 0.05$ was considered statistically significant.

Results

Baseline characteristics of the patients

A total of 120 patients with traumatic forearm bone defects were included in this study, including 60 cases who underwent FFF reconstruction (FFF group) and 60 who underwent ICBG reconstruction (ICBG group). After PSM, most baseline characteristics were well balanced between the two groups (**Table 1**). There were no significant differences in age, sex, BMI, smoking history, diabetes mellitus, hypertension history, injury cause, Gustilo classification, defect location, vascular injury, nerve injury, and tendon injury between the two groups (all $P > 0.05$). However, defect length remained

significantly different between the groups, with the FFF group showing longer defects than the ICBG group (8.25 ± 1.73 cm vs. 6.83 ± 1.09 cm, $P < 0.001$).

The Kaplan-Meier curve analysis (**Figure 2**) showed that the cumulative probability of bone union increased progressively during follow-up time in both groups. The log-rank test revealed a significant difference in time of bone union between the two groups (Log-rank $P = 0.005$). In addition, comparison of bone resorption rate (**Figure 3**) further showed that the bone resorption rate in the FFF group was significantly lower than that of the ICBG group (median 7.35% vs. 13.79%, $P < 0.001$).

Surgical and perioperative indicators

The operative duration was significantly longer in the FFF group than in the ICBG group (272.78 ± 35.99 min vs. 239.27 ± 35.19 min, $P < 0.001$). No significant differences were observed between the two groups regarding postoperative hospital stay (18.02 ± 5.12 vs. 18.62 ± 5.66 days, $P = 0.595$) or duration of donor-site drainage (4.08 ± 1.32 vs. 4.02 ± 1.37 days, $P = 0.813$) (**Table 2**).

FFF vs. ICBG for forearm bone defects

Table 1. Comparison of baseline characteristics between the two groups (matched cohort)

Variable	FFF (n = 60)	ICBG (n = 60)	U/ χ^2	P value
Age (years)	43.88±9.66	45.67±9.76	1644.000	0.414
BMI (kg/m ²)	25.08±2.79	24.82±2.96	1898.500	0.607
Defect length (cm)	8.25±1.73	6.83±1.09	2700.500	<0.001
Time to reconstruction (days)	51.68±24.16	56.43±22.45	1589.500	0.270
Previous surgery count	0.75±0.84	0.65±0.82	1924.000	0.478
Sex			1.302	0.254
Female	15 (25.0%)	9 (15.0%)		
Male	45 (75.0%)	51 (85.0%)		
Smoking			0.323	0.570
No	36 (60.0%)	40 (66.7%)		
Yes	24 (40.0%)	20 (33.3%)		
Diabetes			0.069	0.793
No	52 (86.7%)	51 (85.0%)		
Yes	8 (13.3%)	9 (15.0%)		
Hypertension			1.165	0.281
No	43 (71.7%)	49 (81.7%)		
Yes	17 (28.3%)	11 (18.3%)		
Cause of injury			2.272	0.518
Traffic accident	27 (45.0%)	25 (41.7%)		
Machine crush	17 (28.3%)	24 (40.0%)		
Fall from height	11 (18.3%)	7 (11.7%)		
Explosion	5 (8.3%)	4 (6.7%)		
Gustilo type			0.760	0.859
Type I	8 (13.3%)	6 (10.0%)		
Type II	15 (25.0%)	15 (25.0%)		
Type IIIA	24 (40.0%)	28 (46.7%)		
Type IIIB/C	13 (21.7%)	11 (18.3%)		
Defect site			1.401	0.496
Radius	34 (56.7%)	35 (58.3%)		
Ulna	17 (28.3%)	20 (33.3%)		
Both bones	9 (15.0%)	5 (8.3%)		
Vascular injury			0.000	1.000
No	48 (80.0%)	48 (80.0%)		
Yes	12 (20.0%)	12 (20.0%)		
Nerve injury			1.819	0.177
No	51 (85.0%)	44 (73.3%)		
Yes	9 (15.0%)	16 (26.7%)		
Tendon injury			3.600	0.058
No	50 (83.3%)	40 (66.7%)		
Yes	10 (16.7%)	20 (33.3%)		

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft; BMI, body mass index.

Bone union

The mean bone union time in the ICBG group was significantly shorter than that in the FFF group (5.00±0.86 months vs. 6.51±1.30

months, P<0.001) (**Table 3**). In contrast, the FFF group demonstrated a significantly lower bone resorption rate compared with the ICBG group (7.04±2.00% vs. 13.80±3.65%, P<0.001).

FFF vs. ICBG for forearm bone defects

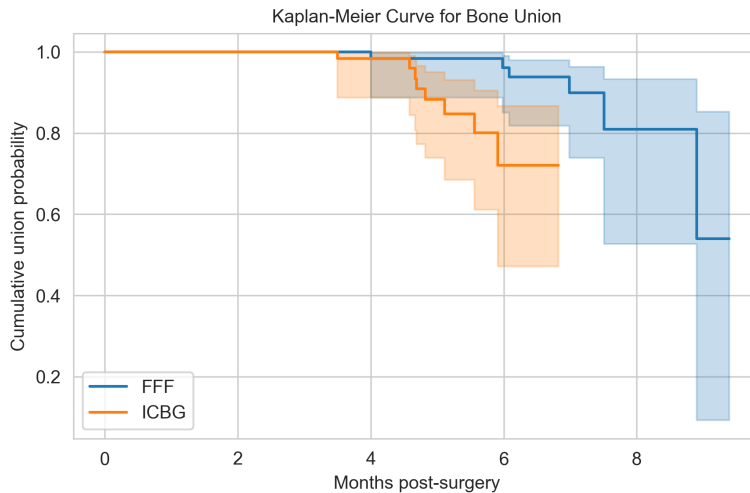


Figure 2. Kaplan-Meier survival curve for bone union time.

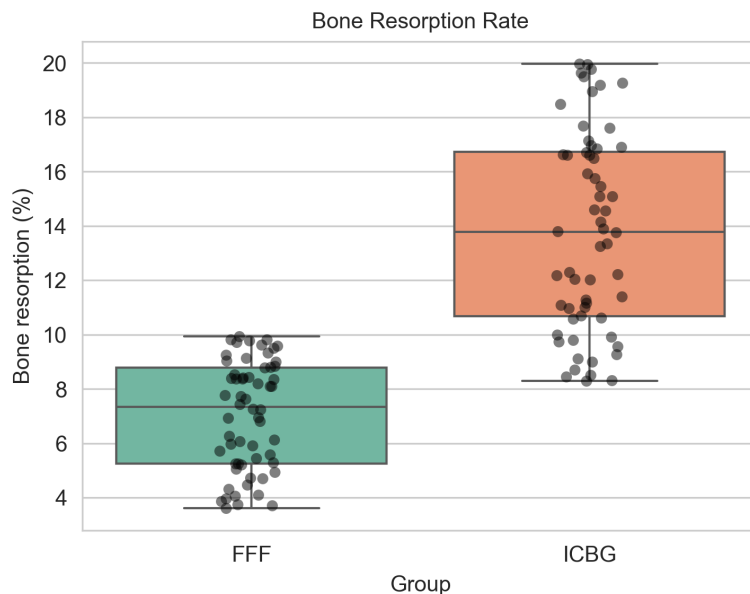


Figure 3. Box plot of bone resorption rate in both groups.

The non-union rate was 10.0% (6/60) in the FFF group and 13.3% (8/60) in the ICBG group, with no significant difference ($P = 0.776$). The re-fracture rate was also comparable between groups ($P = 1.000$). Similarly, no significant difference was found in the secondary surgery rate (13.3% [8/60] vs. 18.3% [11/60], $P = 0.617$).

The scatter plot analysis (**Figure 4**) demonstrated no significant linear correlation between defect length and bone union time in both groups ($r = -0.05$ for the FFF group and $r = 0.05$ for the ICBG group).

Upper limb functional recovery

At 12 months after surgery, no significant difference was observed in the DASH score between the two groups (mean difference: -1.61 , 95% CI: -4.05 to 0.84 ; $P = 0.257$) (**Table 4**). The violin plot (**Figure 5**) showed substantial overlap in DASH score distributions between the two groups. The grip strength ratio (affected side/contralateral side) was significantly higher in the FFF group than in the ICBG group (0.82 ± 0.08 vs. 0.76 ± 0.09 , $P < 0.001$). Wrist range of motion, assessed as the total arc of palmar flexion and dorsal extension, was similar between the two groups ($109.53 \pm 14.83^\circ$ vs. $107.05 \pm 16.42^\circ$, $P = 0.386$). However, the forearm rotation range (total arc of pronation + supination) in the FFF group was significantly greater than that in the ICBG group ($132.12 \pm 14.91^\circ$ vs. $120.27 \pm 18.53^\circ$, $P = 0.001$). The standardized functional recovery radar chart (**Figure 6**) further demonstrated differences between groups in both grip strength and forearm rotation outcomes.

Donor-site complications

The incidence of gait abnormality (16.7% vs. 1.7%, $P = 0.011$) and donor area weakness (20.0% vs. 3.3%, $P = 0.010$) was significantly higher in the FFF group than in the ICBG group. In contrast, the incidence of chronic pain was marginally higher in the ICBG group (15.0% vs. 3.3%, $P = 0.058$). No significant differences were observed between groups in sensory disturbance (16.7% vs. 13.3%, $P = 0.798$), abdominal wall hernia/protrusion (0 vs. 5.0%, $P = 0.242$), or donor-site wound complications (5.0% vs. 11.7%, $P = 0.322$). Overall, gait abnormalities and donor-site weakness were more frequently observed after fibular harvest,

FFF vs. ICBG for forearm bone defects

Table 2. Comparison of operative and perioperative outcomes between the two groups

Variable	FFF (n = 60)	ICBG (n = 60)	U	P value
Operation time (min)	272.78±35.99	239.27±35.19	2670.500	<0.001
Hospital stays (days)	18.02±5.12	18.62±5.66	1698.500	0.595
Donor-site drainage days	4.08±1.32	4.02±1.37	1844.500	0.813

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft.

Table 3. Comparison of bone union outcomes between the two groups

Variable	FFF (n = 60)	ICBG (n = 60)	U/ χ^2	P value
Union time (months)	6.51±1.30	5.00±0.86	2990.500	<0.001
Bone resorption (%)	7.04±2.00	13.80±3.65	143.000	<0.001
Nonunion			0.081	0.776
No	54 (90.0%)	52 (86.7%)		
Yes	6 (10.0%)	8 (13.3%)		
Re-fracture			0.000	1.000
No	57 (95.0%)	57 (95.0%)		
Yes	3 (5.0%)	3 (5.0%)		
Secondary surgery			0.250	0.617
No	52 (86.7%)	49 (81.7%)		
Yes	8 (13.3%)	11 (18.3%)		

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft.

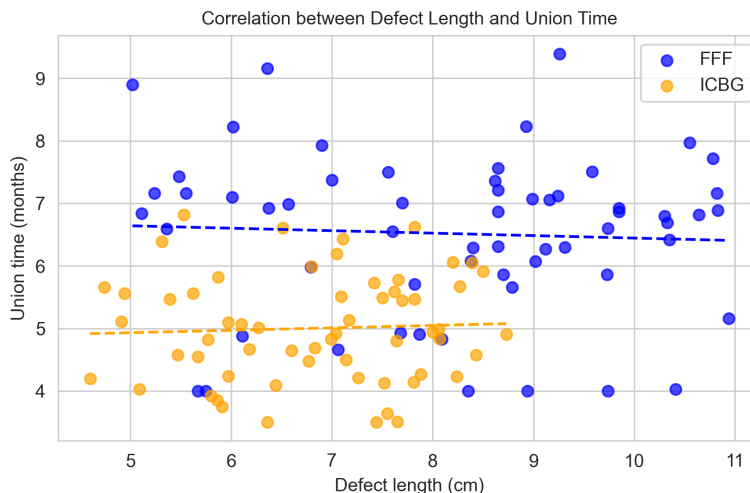


Figure 4. Scatter plot with linear regression lines showing the association between defect length and bone union time in the two groups.

whereas chronic pain and wound complications were relatively more common after iliac crest harvesting (Table 5).

Subgroup analysis according to defect length (Table 6) revealed that among patients with defects ≥ 6 cm, chronic pain was less frequent in the FFF group than in the ICBG group (1.9% vs. 16.7%, $P = 0.030$), whereas gait abnormali-

ty rate (17.3% vs. 2.4%, $P = 0.046$) and donor-site weakness (21.2% vs. 0%, $P = 0.004$) remained significantly more common in the FFF group. Abdominal wall hernia/protrusion occurred only in the ICBG group (7.1%). In patients with defect lengths <6 cm, no significant differences were observed in donor-site complications between the two groups.

Multivariate Logistic regression analysis adjusted for age, smoking history, and defect length (Table 7; Figure 7) showed that ICBG was independently associated with a lower risk of gait abnormality compared with FFF (OR = 0.103, 95% CI: 0.012-0.923, $P = 0.042$). The association between ICBG and chronic pain showed a trend toward increased risk but did not reach statistical significance (OR = 5.356, 95% CI: 0.815-35.18, $P = 0.081$). Due to the absence of abdominal wall hernia/protrusion in the FFF group, multivariable regression analysis for this outcome could

FFF vs. ICBG for forearm bone defects

Table 4. Comparison of upper limb function between the two groups at postoperative 12 months

Variable	FFF (n = 60)	ICBG (n = 60)	Mean difference (95% CI)	P value
DASH score (0-100)	19.62±6.42	21.23±7.09	-1.61 (-4.05-0.84)	0.195
Grip ratio (affected/contralateral)	0.82±0.08	0.76±0.09	0.06 (0.03-0.09)	<0.001
Wrist motion (flexion + extension, °)	109.53±14.83	107.05±16.42	2.49 (-3.17-8.14)	0.386
Forearm rotation (pronation + supination, °)	132.12±14.91	120.27±18.53	11.85 (5.77-17.93)	<0.001

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft; DASH, Disabilities of the Arm, Shoulder and Hand; CI, confidence interval; SD, standard deviation.

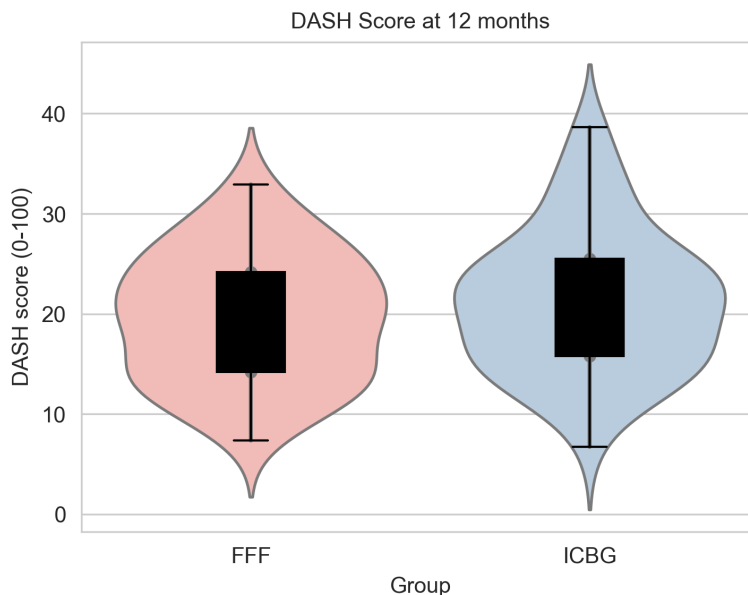


Figure 5. Violin plot showing the comparison of DASH scores between two groups at postoperative 12 months. Notes: DASH, Disabilities of the Arm, Shoulder and Hand; FFF, free fibular flap; ICBG, iliac crest bone graft.

not be performed, and only descriptive results were reported.

The heatmap analysis for gait abnormality in the FFF group (**Figure 8**) showed that higher rates of gait abnormality were observed among younger patients (20-40 years old) and those with lower BMI (18-24 kg/m²).

Multivariate linear regression of bone healing time

A multivariable linear regression model was constructed with bone union time (months) as the dependent variable, and graft type, age, smoking history, defect length, and Gustilo classification (III/IV vs. I/II) as independent variables. The analysis showed that the ICBG group had a significantly shorter bone union time compared to the FFF group ($\beta = -1.52$

month, 95% CI: -1.97 to -1.06, $P < 0.001$). None of the other included variables were significantly associated with bone union time (all $P > 0.05$) (**Table 8**).

Discussion

This retrospective matched cohort study systematically compared the clinical outcomes and donor-site complications of FFF and ICBG reconstruction for traumatic segmental forearm bone defects. The major findings were as follows: (1) ICBG was associated with significantly shorter bone union time than FFF, with an average difference of approximately of 1.5 months; however, ICBG demonstrated a significantly higher bone

resorption rate; (2) No significant differences were observed between groups in nonunion rate, re-fracture rate, and secondary surgery rate; (3) FFF was associated with better grip strength ratio and forearm rotation range; (4) Donor-site complications differed between the two strategies: FFF was more frequently associated with gait abnormalities and donor-site weakness, while ICBG showed a tendency toward higher rates of chronic pain and abdominal wall hernia/protrusion, and these differences were more prominent in cases with longer defects (≥ 6 cm). These findings provide clinically relevant evidence to support individualized graft selection for traumatic segmental forearm bone reconstruction.

In this study, the average bone union time in the ICBG group was 5.0 months, significantly

FFF vs. ICBG for forearm bone defects

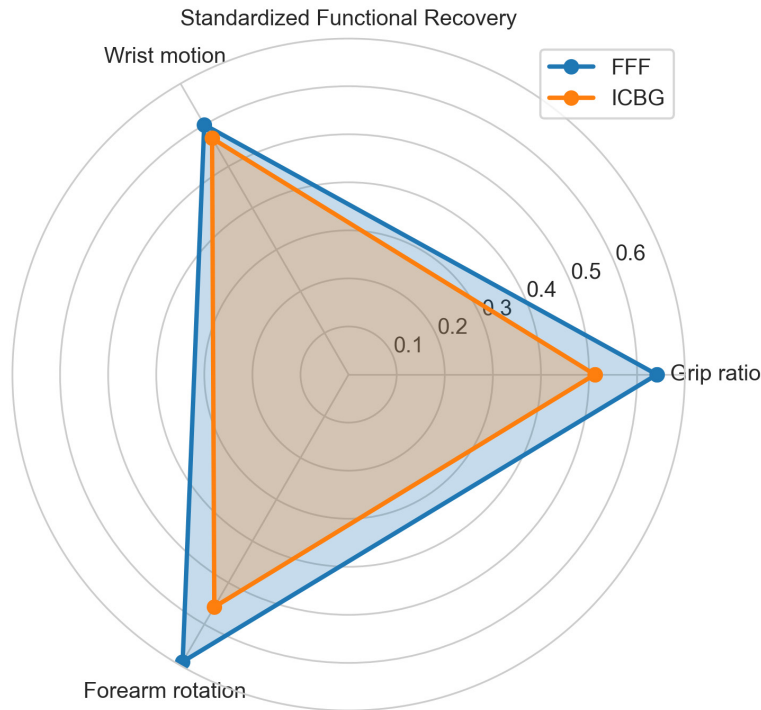


Figure 6. Radar chart of standardized functional recovery (grip ratio, wrist motion, forearm rotation).

Table 5. Comparison of donor-site complications between the two groups

Complication	FFF (n = 60)	ICBG (n = 60)	χ^2	P value
Chronic pain	2 (3.3%)	9 (15.0%)	3.603	0.058
Gait abnormality	10 (16.7%)	1 (1.7%)	6.405	0.011
Sensory disturbance	10 (16.7%)	8 (13.3%)	0.065	0.798
Donor-site weakness	12 (20.0%)	2 (3.3%)	6.550	0.010
Hernia/abdominal bulge	0 (0.0%)	3 (5.0%)	1.368	0.242
Wound complication	3 (5.0%)	7 (11.7%)	0.982	0.322

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft; SD, standard deviation.

shorter than 6.5 months in the FFF group. This difference may be attributed to the biological characteristics of iliac crest grafts, which contain abundant cancellous bone and bone marrow-derived mesenchymal stem cells, providing a favorable environment for early osteogenesis and incorporation [22]. Previous studies have reported union times of approximately 4-6 months for ICBG reconstruction and 6-8 months for FFF reconstruction in forearm bone defects [23]. However, the bone resorption rate in ICBG group (13.8%) was significantly higher than that in the FFF group (7.0%). Although cancellous bone undergoes rapid revascularization and remodeling, it may be more suscep-

tible to volume loss in the forearm that bears shear and torsional stresses [24]. In contrast, the vascularized fibula graft provides a living cortical bone structure with sustained blood supply, which is conducive to maintaining graft volume, bone length, and mechanical alignment over time, especially suitable for cases requiring joint surface reconstruction or precise alignment [25]. Despite the difference in bone resorption rates, long-term clinical outcomes were comparable between the two groups, with no significant differences in non-union rate (10.0% for FFF vs. 13.3% for ICBG), re-fracture rate (both 5.0%), and secondary surgery rate (13.3% vs. 18.3%).

Although no significant difference was observed in DASH scores between the two groups, objective functional indicators showed that the grip strength ratio (0.82 vs. 0.76) and the forearm rotation range (132° vs. 120°) in the FFF group were significantly better than those in the ICBG group. These findings may be associated with the biomechanical properties of the fibular graft. The fibula provides a

vascularized cortical bone structure with high mechanical strength and resistance to torsional forces, which may facilitate early rehabilitation and reduce the risk of alignment loss caused by graft resorption [26, 27]. Additionally, the relatively long vascular pedicle of the FFF allows greater flexibility in recipient vessel selection and flap positioning, which may help preserve the functional anatomy of the forearm [28]. In contrast, the iliac bone flap is softer with poorer stability after internal fixation. Concerns regarding graft incorporation or resorption may also influence the progression of rehabilitation in some patients [29]. It is worth noting that there was no significant dif-

FFF vs. ICBG for forearm bone defects

Table 6. Subgroup analysis of donor-site complications by defect length

Subgroup	Complication	FFF rate (%)	ICBG rate (%)	χ^2	P value
≥6 cm	Chronic pain	1.9	16.7	4.731	0.030
	Gait abnormality	17.3	2.4	3.988	0.046
	Sensory disturbance	19.2	14.3	0.128	0.720
	Donor-site weakness	21.2	0.0	8.119	0.004
	Hernia/bulge	0.0	7.1	1.873	0.171
	Wound complication	5.8	11.9	0.474	0.491
<6 cm	Chronic pain	12.5	11.1	0.000	1.000
	Gait abnormality	12.5	0.0	0.181	0.671
	Sensory disturbance	0.0	11.1	0.034	0.854
	Donor-site weakness	12.5	11.1	0.000	1.000
	Wound complication	0.0	11.1	0.034	0.854

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft; SD, standard deviation.

Table 7. Multivariable logistic regression analysis for donor site complications

Outcome	Variable	OR (95% CI)	P value
Chronic pain	Intercept	0.002 (0.000-1.295)	0.060
	Group (ICBG vs. FFF)	5.356 (0.815-35.180)	0.081
	Age (per year)	1.044 (0.974-1.118)	0.223
	Smoking (Yes vs. No)	0.187 (0.022-1.607)	0.127
	Defect length (per cm)	1.154 (0.645-2.064)	0.630
Gait abnormality	Intercept	0.038 (0.000-5.816)	0.203
	Group (ICBG vs. FFF)	0.103 (0.012-0.923)	0.042
	Age (per year)	1.009 (0.942-1.081)	0.792
	Smoking (Yes vs. No)	1.478 (0.373-5.858)	0.578
	Defect length (per cm)	1.139 (0.748-1.734)	0.544

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft; OR, odds ratio; CI, confidence interval.

ference in wrist range of motion between the two groups (109° vs. 107°), suggesting that both bone flaps have a relatively small impact on the wrist joint. This may be explained by the fact that most defects are involved the diaphyseal region rather than the articular surface.

An important finding of this study was that the two reconstruction strategies demonstrated different complication profiles, and these differences appeared to be more evident among patients with longer defects. In the FFF group, gait abnormalities (16.7%) and donor-site weakness (20.0%) were the predominant complications and occurred more frequently than in the ICBG group. These complications may be related to alterations in ankle biomechanics and muscle-tendon function following fibular harvest, including potential effects on lateral ankle

stability and structures associated with great toe flexion [30-32]. Multivariate regression analysis further confirmed that the risk of gait abnormalities was significantly lower in the ICBG group (OR = 0.103, P = 0.042). Interestingly, the heatmap analysis showed that younger patients (20-40 years old) and those with a lower BMI (18-24 kg/m²) in the FFF group tended to show higher incidence of gait abnormalities [4, 33]. For patients requiring high levels of lower-extremity function, such as frequent running,

jumping, or heavy physical activity, the potential impact of fibular donor-site morbidity should be carefully considered during surgical planning.

In contrast, the predominant concern of the iliac bone flap is chronic pain at the donor site (15.0%) and abdominal wall hernia/protrusion (5.0%). Chronic pain after iliac bone harvesting is mostly related to periosteal disruption, and injury to the surrounding musculature, and irritation of local sensory structures [34]. In this study, although the difference in chronic pain incidence between groups did not reach statistical significance (P = 0.058), the observed difference may still be clinically relevant. Notably, among patients with a defect length of ≥6 cm, this difference became significant (1.9% in the fibula flap group vs. 16.7% in the iliac bone flap

FFF vs. ICBG for forearm bone defects

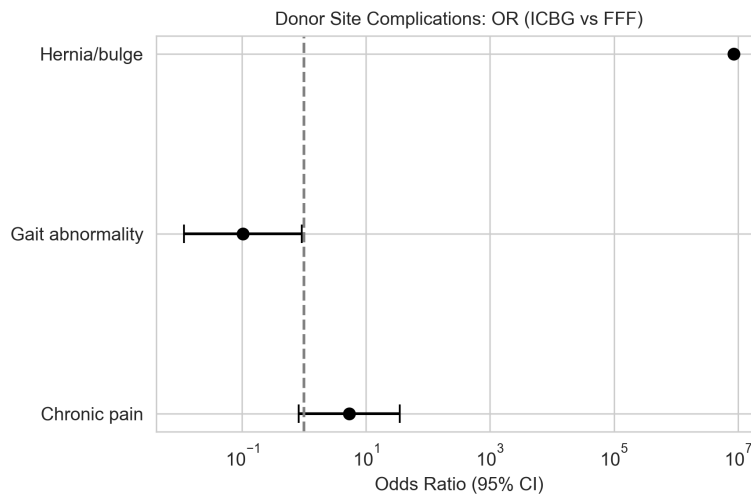


Figure 7. Forest plot of multivariable logistic regression for donor site complications (OR with 95% CIs). Notes: OR, odds ratio; CI, confidence interval.

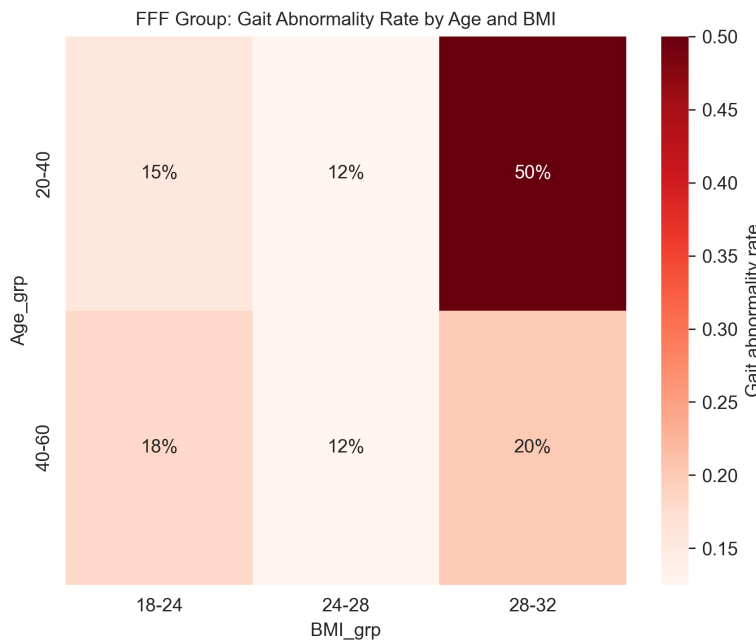


Figure 8. Heatmap of gait abnormality rate stratified by age and BMI in the FFF group. Notes: BMI, body mass index; FFF, free fibular flap.

group, $P = 0.030$). Abdominal wall hernia/protrusion was only seen in the ICBG group (3 cases, 5.0%), and all affected patients had relatively extensive iliac crest harvesting. No significant differences were observed between groups regarding other complications, such as sensory disorders or wound problems.

The subgroup analysis provides additional clinical insights. Among patients with defects ≥ 6

cm, FFF reconstruction was associated with a lower incidence of chronic pain (1.9%) but a higher incidence of gait abnormality and donor-site weakness (16.7%) compared with ICBG. These findings suggest that, for extensive bone defects, FFF may provide adequate bone support while avoiding risk of chronic donor-site pain at the cost of an increased probability of lower limb dysfunction. On the contrary, in patients with limited lower-extremity functional reserve, such as older individuals or those with pre-existing balance impairment, ICBG may represent an alternative option even for larger defects; however, the potential risks of chronic pain and abdominal wall complications should be considered during shared decision-making.

This study is one of the relatively large matched cohort studies directly comparing FFF and ICBG reconstruction for forearm bone defects. Previous small-sample studies often failed to perform PSM and lacked adequate control of confounding factors [35]. In this study, we matched key variables such as age and defect length to enhance the comparability between the two groups. Additionally, donor-site complications were systematically evaluated and categorized

according to their different types of manifestations, while previous studies frequently reported donor-site morbidity in a less differentiated manner [31]. In addition, the heatmap analysis provided a visual representation of the distribution patterns of gait abnormalities among FFF recipients across age and BMI subgroups, which may assist in identifying potential patient characteristics associated with donor-site functional concerns.

Table 8. Multivariable linear regression analysis for bone union time

Variable	β (95% CI)	P value
Intercept	7.80 (6.21 - 9.40)	<0.001
Group (ICBG vs. FFF)	-1.52 (-1.97 - -1.06)	<0.001
Age (per year)	-0.02 (-0.04 - 0.00)	0.065
Smoking (Yes vs. No)	-0.12 (-0.55 - 0.31)	0.586
Defect length (per cm)	-0.03 (-0.17 - 0.12)	0.702
Gustilo type (III/IV vs. I/II)	-0.26 (-0.68 - 0.15)	0.209

Notes: FFF, free fibular flap; ICBG, iliac crest bone graft; CI, confidence interval; SD, standard deviation.

This study does have several limitations. First, the retrospective design inevitably introduces selection bias and residual confounding. Although PSM was employed, unmeasured confounding factors, such as the degree of soft tissue injury, vascular status, rehabilitation protocols, and surgeon preference, may have influenced treatment selection and outcomes. Second, defect length remained significantly different between groups, with longer defects observed in the FFF group. Although it was adjusted for in the multivariate regression analysis, residual effects of this imbalance cannot be completely excluded. Third, the follow-up period (12-18 months) may be insufficient for observing long-term bone resorption, complications after implant removal, and late donor-site musculoskeletal problems. Fourth, upper-limb functional assessment was based on commonly used clinical measures but did not include more detailed evaluations (e.g., endurance during load-bearing activities, fine motor dexterity). Finally, as a single center study, the generalizability of the findings may be limited. Future multi-center, prospective studies with larger cohorts and longer follow-up are warranted to validate these results.

Based on the findings of this study, an individualized decision-making framework may be considered: (1) For patients with defects ≥ 6 cm, particularly those with high demands for forearm rotation and grip strength, and who are willing to accept potential lower-extremity donor-site morbidity, FFF should be the preferred option; (2) For patients with defects < 6 cm, those requiring earlier radiographic union, those with limited tolerance for lower limb functional impairment (such as the elderly or athletes), or those with potential risk factors for abdominal wall complications (such as having

multiple pregnancies or obesity), ICBG may represent an alternative option; (3) Regardless of graft selection, the expected incidence of complications at the donor site should be fully disclosed to the patients before the operation, including the potential risk of gait abnormalities and donor-site weakness after fibular harvest, as well as chronic pain and abdominal wall complications after iliac crest harvesting.

Conclusion

Both FFF and ICBG reconstruction can effectively reconstruct segmental bone defects in the forearm after trauma. However, there are significant differences in efficacy and the donor-site complication profiles between the two techniques. ICBG is associated with faster bone union but a higher bone resorption rate and a tendency toward chronic pain and abdominal wall hernia at the donor site. FFF provides advantages in maintaining graft volume and improving selected functional outcomes, such as grip strength and forearm rotation, but is associated with a higher incidence of gait abnormality and donor-site weakness. Therefore, graft selection should be individualized based on defect length, functional requirements, patient comorbidities, and acceptance of potential donor-site morbidity.

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Disclosure of conflict of interest

None.

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