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"Fate of pressure-bearing flaps: long-term observations"

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The plantar (weight-bearing) regions of the foot are particularly susceptible to biomechanical stress, placing them at elevated risk for chronic ulceration following surgical reconstruction. This study evaluates the incidence and risk factors for ulceration after free-flap coverage of foot defects, with a focus on anatomical location and mechanical loading. A retrospective review was conducted involving 90 patients who underwent foot free-flap reconstruction between 2015 and 2022, with at least two years of follow-up. Foot defects were categorized into pressure-bearing (plantar) and non-pressure-bearing (dorsal) zones and further subdivided into seven anatomical subunits. Flap survival was 93.3%. Ulceration occurred in 25 patients (27.8%), with significantly higher rates in plantar regions (42.9%) compared to dorsal regions (9.8%) ($p = 0.001$). Plantar ulcers developed later postoperatively, were more severe (Wagner grade ≥ 3 in 15 cases), and often required surgical interventions, including three amputations. Dorsal ulcers were milder and resolved with conservative care. Subunit analysis showed the forefoot, particularly medial and lateral areas, had the highest ulceration rates. Multivariate analysis identified plantar location as the only independent predictor of ulceration (OR 6.191, $p = 0.008$). These findings underscore the importance of anatomical considerations in planning and long-term monitoring of plantar foot reconstructions to minimize ulceration risks.

Soft tissue reconstruction of the foot, particularly in weight-bearing regions, such as the plantar forefoot and heel, presents persistent challenges due to the unique anatomical and biomechanical properties of the region. Plantar surface is characterized by a thick glabrous skin, fibrous septa that anchor the dermis to the underlying plantar fascia, and dense subcutaneous fat lobules that collectively resist compression and shear during ambulation[1].

These adaptations enable the foot to withstand substantial pressure but also complicate reconstructive efforts, especially in the presence of chronic wounds or systemic comorbidities. In contrast, the dorsal surface is traditionally considered non-weight-bearing but remains vulnerable to friction-related ulceration during shoe wearing, particularly in patients with neuropathy. Thus, both plantar and dorsal regions demand durable reconstructive strategies that account not only for vascular viability but also for long-term biomechanical endurance and defects in weight-bearing regions, posing persistent challenges in reconstructive surgery.

Free tissue transfer has emerged as the mainstay technique for covering complex foot defects, particularly when local options are limited or when deep, infected, or recurrent wounds are present. Microsurgical flaps provide a well-vascularized, pliable tissue that facilitates wound resolution and limb salvage in high-risk patients. Although numerous studies have demonstrated excellent short-term flap survival and limb salvage rates[1,2], long-term outcomes in high-stress regions, particularly the incidence of postoperative ulceration and structural failure, have received comparatively less attention. Recurrent ulceration in reconstructed plantar zones remains a clinically significant concern, especially in patients with diabetes mellitus, peripheral arterial occlusive disease (PAOD), or chronic renal failure, all of which impair wound healing and predispose patients to tissue breakdown[1,3].

Recently, the need to tailor reconstructive strategies to the specific biomechanical demands of the foot has been increasingly recognized. The foot comprises multiple functional subunits, each of which is exposed to different magnitudes and patterns of pressure during the gait cycle. The forefoot and heel are considered the primary load-bearing regions and are associated with an increased risk of flap breakdown and ulceration under repetitive stress. Conversely, the midfoot and dorsal areas experience comparatively less direct pressure but are not exempt from complications[1,4]. Thinner contour-adaptive flaps offer improved outcomes in high-pressure areas, enabling early ambulation while minimizing bulk-related complications and frictional trauma[5]. Nevertheless, few studies have systematically evaluated the risk of ulceration across anatomical subunits or correlated site-specific mechanical loading with long-term flap durability.

In this study, we aimed to evaluate the long-term outcomes of free-flap reconstruction for foot defects, with a specific focus on the incidence of ulceration and its contributing risk factors. We analyzed a consecutive cohort

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of patients who underwent free-flap reconstruction for foot defects with a minimum follow-up of two years. By integrating the anatomical, biomechanical, and clinical perspectives, this study aimed to provide evidence-based insights for optimizing flap selection and improving reconstructive outcomes in biomechanically demanding foot regions.

Methods

A retrospective review was conducted of patients who underwent free-flap reconstruction for foot defects at a single institution between January 2015 and December 2022. This study was approved by the Institutional Review Board (SEUMC 2025-06-005) and the requirement for informed consent was waived by the Institutional Ethics Committee of Ewha Womans University Seoul Hospital, Korea and all methods were performed in accordance with the relevant guidelines and regulations. All surgeries were performed by a single surgeon (P.B.Y). The inclusion criteria were (1) free flap coverage for foot wounds and (2) a minimum clinical follow-up duration of two years. Patients with incomplete medical records or follow-up periods less than two years were excluded from the analysis.

Patient demographic variables, including age, sex, wound etiology (diabetes mellitus, trauma, infection, oncologic resection), presence of comorbidities such as peripheral arterial occlusive disease (PAOD) or chronic renal failure, and presence of underlying bone abnormalities, were retrospectively collected. Surgical variables were analyzed including, flap type (anterolateral thigh [ALT], deep inferior epigastric perforator [DIEP], latissimus dorsi musculocutaneous [LDMC], thoracodorsal artery perforator [TDAP], and superficial circumflex iliac artery perforator [SCIP] flaps), flap dimensions, recipient vessels, and performance of adjunctive procedures such as percutaneous transluminal angioplasty (PTA).

The outcome variables evaluated included flap survival, occurrence of ulceration during follow-up, ulcer location, depth, onset time, number of ulcerations, need for surgical re-intervention, and final limb status (salvage or amputation).

Anatomical subunit classification

To descriptively account for anatomical and functional variability across the foot, defects were categorized using a subunit-based anatomical mapping adapted from previously published reconstructive and diabetic foot literature[1,3,6]. The foot was initially divided into two broad regions: plantar surfaces, which are generally regarded as pressure-bearing areas, and dorsal surfaces, which are considered non–pressure-bearing regions. For analytical purposes, five principal subunits were defined (Fig. 1): the dorsum, forefoot, midfoot, heel and mixed regions. A further refined classification delineated seven distinct anatomical regions (Fig. 2) involving multiple zones: the dorsum, central lateral forefoot, central medial forefoot, lateral forefoot, medial forefoot, heel, and mixed regions. This subunit classification was applied as a descriptive anatomical mapping framework, rather than as a novel biomechanical model. Comparative analyses were performed across these subunits to evaluate the association between defect location and long-term flap-related outcomes, with a particular focus on ulcer development.

Ulcer definition and management

For time-to-event analyses, ulcer-free survival was defined as the interval from free flap reconstruction to the first documented ulceration. Only the first ulcer event was included in Kaplan–Meier and Cox regression analyses. Subsequent ulcer recurrences were recorded clinically but were not modeled as repeated events.

Management of ulceration followed a stepwise approach. Initial treatment consisted of conservative wound management, including local wound care, offloading, and infection control when indicated. Surgical re-intervention was considered when ulcers failed to respond to conservative management, recurred repeatedly, or were associated with exposure of critical structures (such as bone or tendon), persistent local infection, or evidence of systemic involvement.

Statistical analysis

Statistical analyses were performed using the R language version 4.4.1 (R Foundation for Statistical Computing, Vienna, Austria) and the TnF program version 4.5 (YooJin BioSoft, Korea). Continuous variables were presented as medians and interquartile ranges, and categorical variables were presented as numbers and percentages. Continuous variables between groups were compared using the Wilcoxon rank-sum test. Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate.

The risk factors associated with ulceration and flap failure were evaluated using univariate and multivariate binary logistic regression models. Survival analysis was performed using Kaplan–Meier curves, and differences between groups were assessed using the log-rank test. The Cox proportional hazards regression model was used to identify the independent predictors of ulceration development over time. Statistical significance was defined as a p-value < 0.05.

Results

Patient characteristics and flap outcomes

Ninety patients who underwent free-flap reconstruction of foot defects were included in this study. The median follow-up duration was 39.5 months (range, 26.8–78.3 months). The cohort included 65 male and 25 female patients, with a median age of 54.0 years. The most common etiologies of the defects were diabetic foot ulcers ($n = 42$, 46.7%), trauma ($n = 40$, 44.4%), and oncological defects ($n = 8$, 8.9%). These data are presented in Table 1.

Comorbidities included diabetes mellitus (53.3%), peripheral arterial occlusive disease (PAOD) (34.4%), and chronic renal failure requiring hemodialysis (10.0%). Underlying bone abnormalities, including osteomyelitis,

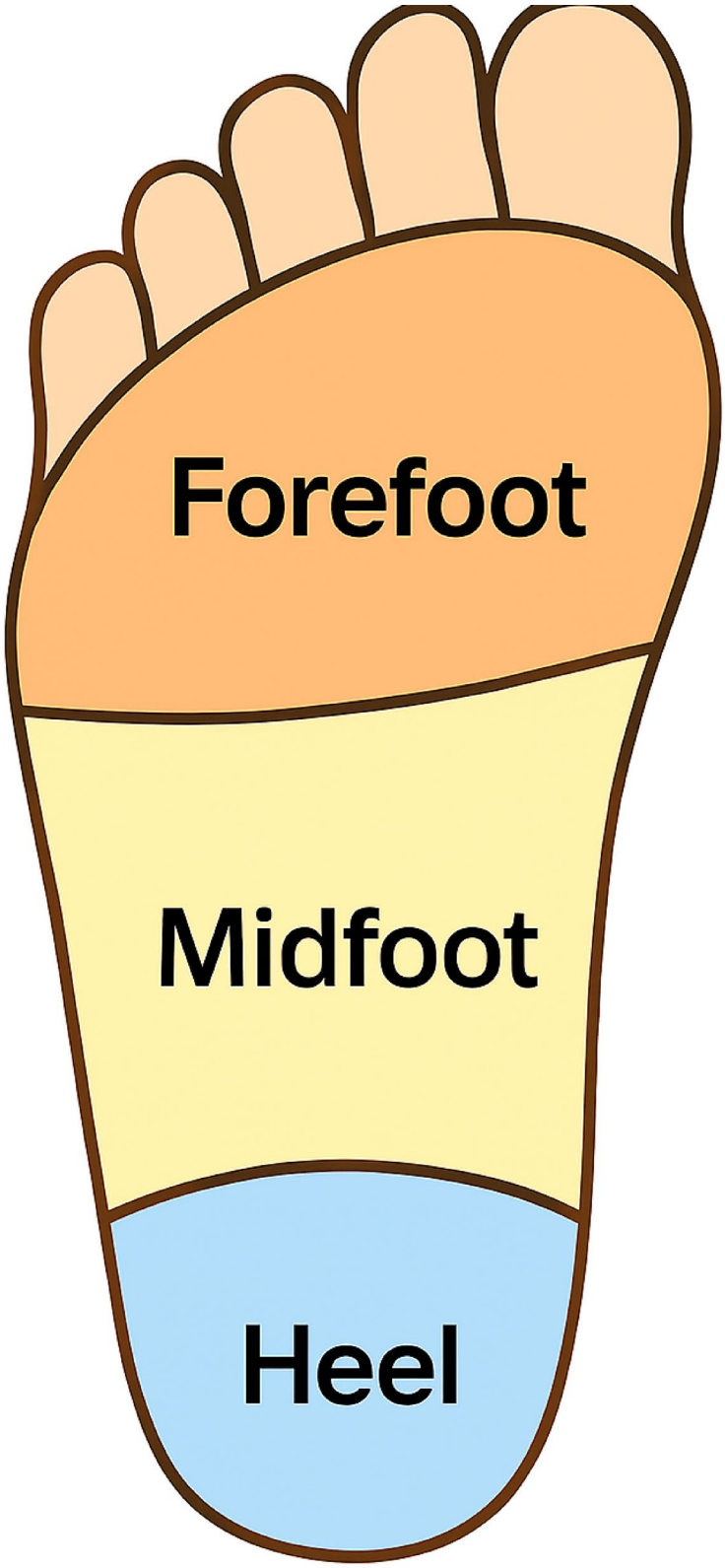


Fig. 1. Schematic representation of the five principal subunits used for analysis: Dorsum, forefoot, midfoot, heel, dorsum, and mixed regions. (For this illustration, only the plantar regions are depicted, as the dorsum is not visualized in the plantar view of the foot.).

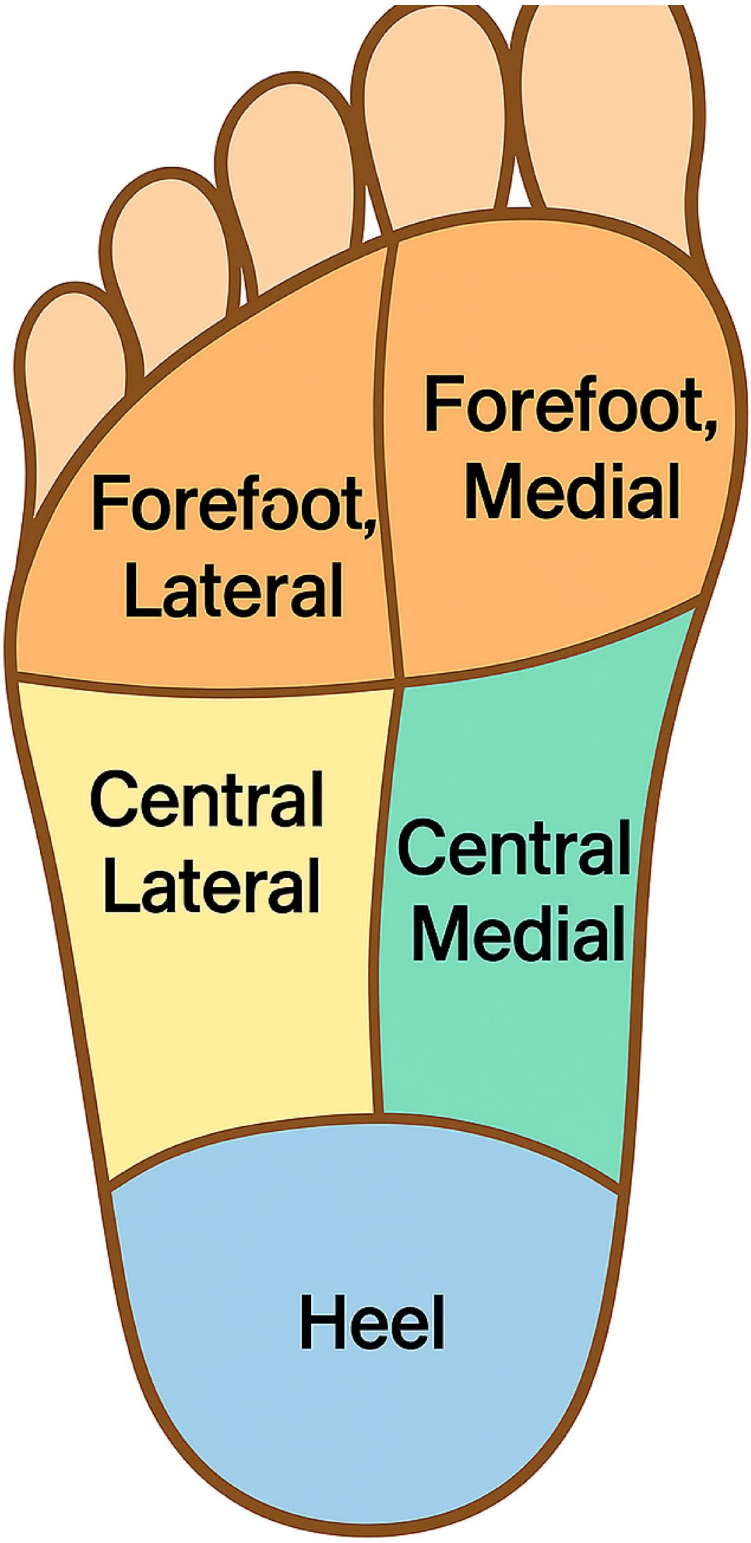


Fig. 2. Schematic representation of the refined seven-region anatomical classification used for analysis: Dorsum, forefoot lateral, forefoot medial, central lateral, central medial, and heel (For this illustration, only the plantar regions are depicted, as the dorsum is not visualized in the plantar view of the foot).

Parameter		Value
No. subjects (male/female)		90 patients (65/25)
Age at the time of surgery (years)		54.0 years(range: 40.5 ~ 62.3)
Mean follow-up(months)		39.5(26.8 ~ 78.3)
Comorbidities		
Diabetes mellitus		48 (53.3%)
Peripheral artery obstructive disease		31 (34.4%)
Etiology		
Trauma		40 (44.4%)
Diabetic foot		42 (46.7%)
Oncologic defect		8 (8.9%)
Comorbid bone disease		56(62.2%)
Location	Dorsum	41(45.6%)
	Plantar	49(54.4%)
Mean flap dimension		49.5(24.50 ~ 80.50)
Flap type	ALT	51(56.7%)
	TDAP	29(32.2%)
	DIEP	3(3.3%)
	SCIP	3(3.3%)
	LDMC	4(4.4%)
Anastomosis type	End-to-end	43(47.8%)
	End-to-side	47(52.2%)
Percutaneous angiography		24(26.7%)

Table 1. Patients' demographics and basic surgical information.

were present in 62.2% of cases. Regarding defect location, 49 cases (54.4%) of the flaps were placed in plantar region, and 41 (45.6%) were in dorsal region. The most frequently used flaps were anterolateral thigh flaps (56.7%) and thoracodorsal artery perforator (TDAP) flaps (32.2%).

The posterior tibial artery (42.2%) and dorsalis pedis artery (50.0%) were the most common recipient vessels. Anastomosis types were evenly distributed between end-to-end (47.8%) and end-to-side (52.2%) techniques. Percutaneous transluminal angioplasty (PTA) was performed preoperatively in 26.7% of cases. Overall, flap success was achieved in 84 of 90 patients (93.3%). Six cases of flap failure required secondary reconstruction.

Ulceration incidence and overall outcomes

Ulceration occurred in 25/90 patients (27.8%) during the follow-up period. Flap location demonstrated a significant association with ulcer development, with 21 cases (84.0%) occurring in plantar flaps and only four cases (16.0%) in dorsal flaps ($p = 0.001$). In the plantar group, ulceration developed at a mean of 8.45 months postoperatively and recurred an average of 2.86 times before achieving wound healing. Ulcer severity was classified using the Wagner grading system as grade 1 ($n = 1$), grade 2 ($n = 5$), grade 3 ($n = 8$), and grade 4 ($n = 7$). Bone involvement was noted in 10 of the 21 plantar ulcer cases (47.6%), all of which required surgical intervention. Complete ulcer healing was achieved in 16 cases, while three patients eventually underwent below-knee amputation due to persistent or recurrent wounds.

In contrast, ulceration in the dorsal group occurred earlier, at a mean of 1.25 months postoperatively, and was notably less severe. Two cases were classified as Wagner Grade 1, and one each was classified as grade 2 or grade 3. Bone involvement was identified in only one case, who required surgical management. All four dorsal ulcerations healed completely, without progression to limb-threatening complications or amputation (Table 2).

In the five-region subunit analysis, forefoot flaps demonstrated the highest incidence of ulceration, accounting for 40.0% of all ulcer cases ($p < 0.001$). Heel and midfoot flaps were less commonly affected, comprising 8.0% and 4.0% of the ulceration group, respectively. Dorsal flaps were significantly protective, accounting for 16.0% of ulcer cases.

The seven-region subunit classification further refines these findings. Flaps involving the medial forefoot subunit were most strongly associated with ulceration, occurring in 28.0% of ulcerated cases ($p < 0.001$). Lateral forefoot was also significantly associated with ulcerations. In contrast, flaps placed in the central subunits (central medial or central lateral) and heel regions demonstrated no significant differences between the groups. Notably, the dorsum-based flaps showed significantly lower ulceration rates ($p < 0.001$).

Although differences in ulceration rates were observed across flap types—ALT flaps were used more frequently in ulcerated cases (48.0%) than TDAP flaps (36.0%), and conventional flaps showed no ulceration, and flap type was not significantly associated with ulceration. Similarly, flap dimension did not differ significantly between groups (median 49.0 cm^2 vs. 49.5 cm^2, $p = 0.692$), nor did recipient vessel type ($p = 0.752$) or anastomosis technique ($p > 0.05$). The use of percutaneous transluminal angioplasty (PTA) also did not significantly correlate with ulceration ($p = 0.657$).(Table 3).

	Subgroup	Plantar	Dorsal	Total	*p*-value
N(%)		21(84%)	4(16%)	25	0.001**
Ulceration onset(month)		8.45	1.25		
Mean number of ulceration		2.86	1.25		
Ulceration depth	Grade I	1	2		
	Grade II	5	1		
	Grade III	8	1		
	Grade IV	7	0		
Bone abnormality		10/21	1/4		
Surgical treatment(cases)		10/21	1/4		
Ulcer healing(cases)		16/21	4/4		
Major amputation(cases)		3	0		

Table 2. Comparison between plantar and dorsal ulceration.

	Subgroup	Ulceration: No	Ulceration: Yes	Total	*p*-value
N(%)		65 (72.2)	25 (27.8)	90	
Flap location: (2 subunits)	Dorsum	37(56.9)	4(16.0)	41(45.6)	0.001
	Plantar	28 (43.1)	21 (84.0)	49 (54.4)	
	Dorsum	37 (56.9)	4 (16.0)	41 (45.6)	< 0.001**
	Forefoot	5 (7.7)	10 (40.0)	15 (16.7)	
Flap location: (5 subunits)	Midfoot	1 (1.5)	1 (4.0)	2 (2.2)	
	Heel	10 (15.4)	2 (8.0)	12 (13.3)	
	Mixed	12 (18.5)	8 (32.0)	20 (22.2)	
Flap location: (7 subunits)	Dorsum	37 (56.9)	4 (16.0)	41 (45.6)	< 0.001**
	Central lateral	0 (0.0)	1 (4.0)	1 (1.1)	
	Central medial	1 (1.5)	0 (0.0)	1 (1.1)	
	Forefoot lateral	3 (4.6)	3 (12.0)	6 (6.7)	
	Forefoot medial	2 (3.1)	7 (28.0)	9 (10.0)	
	Heel	10 (15.4)	2 (8.0)	12 (13.3)	
	Mixed	12 (18.5)	8 (32.0)	20 (22.2)	
	Dorsalis pedis	31 (47.7)	14 (56.0)	45 (50.0)	0.752
Recipient vessel	Posterior tibial A	29 (44.6)	9 (36.0)	38 (42.2)	
	Others	5 (7.7)	2 (8.0)	7 (7.8)	
Flap type 1	TDAP	30.8%	36.0%	32.2%	0.136
	ALT	60.0%	48.0%	56.7%	
	DIEP	1.5%	8.0%	3.3%	
	LDMC	6.2%	0.0%	4.4%	
	SCIP	1.5%	8.0%	3.3%	
Flap type 2	LDMC	4 (6.2%)	0 (0.0%)	4 (4.4%)	0.573
	Perforator flaps	61 (93.8%)	25 (100.0%)	86 (95.6%)	
Flap dimension		49.50 (33.50 ~ 80.50)	49.00 (24.50 ~ 79.38)	49.50 (32.00 ~ 78.75)	0.692

Table 3. Comparison of surgical variables according to ulceration.

Kaplan–Meier survival analysis demonstrated significantly lower ulceration-free survival rates in flaps located in the pressure-bearing plantar regions than in those located in the dorsal regions (log-rank $p < 0.001$). Plantar flaps exhibit a continuous decline in ulceration-free survival beginning within the first year, with cumulative survival falling below 50% in 72 months. In contrast, dorsal flaps maintained > 70% ulceration-free survival even at 120 months, indicating superior long-term stability (Fig. 3).

The five-group subunit analysis reinforced these findings. Forefoot and midfoot flaps had significantly lower ulceration-free survival rates than heel and dorsal flaps, with most ulceration events occurring within the first 60 months postoperatively ($p < 0.001$) (Fig. 4).

Further stratification by anatomical subunits revealed distinct patterns in survival probability. Forefoot flaps, particularly those involving the medial and lateral subunits, are associated with the earliest and most pronounced decline in ulceration-free survival. The medial region of the forefoot demonstrated the steepest decrease within the first 24–36 months. The heel and central forefoot flaps showed an intermediate risk, whereas the dorsal flaps demonstrated favorable long-term outcomes ($p < 0.001$) (Fig. 5).

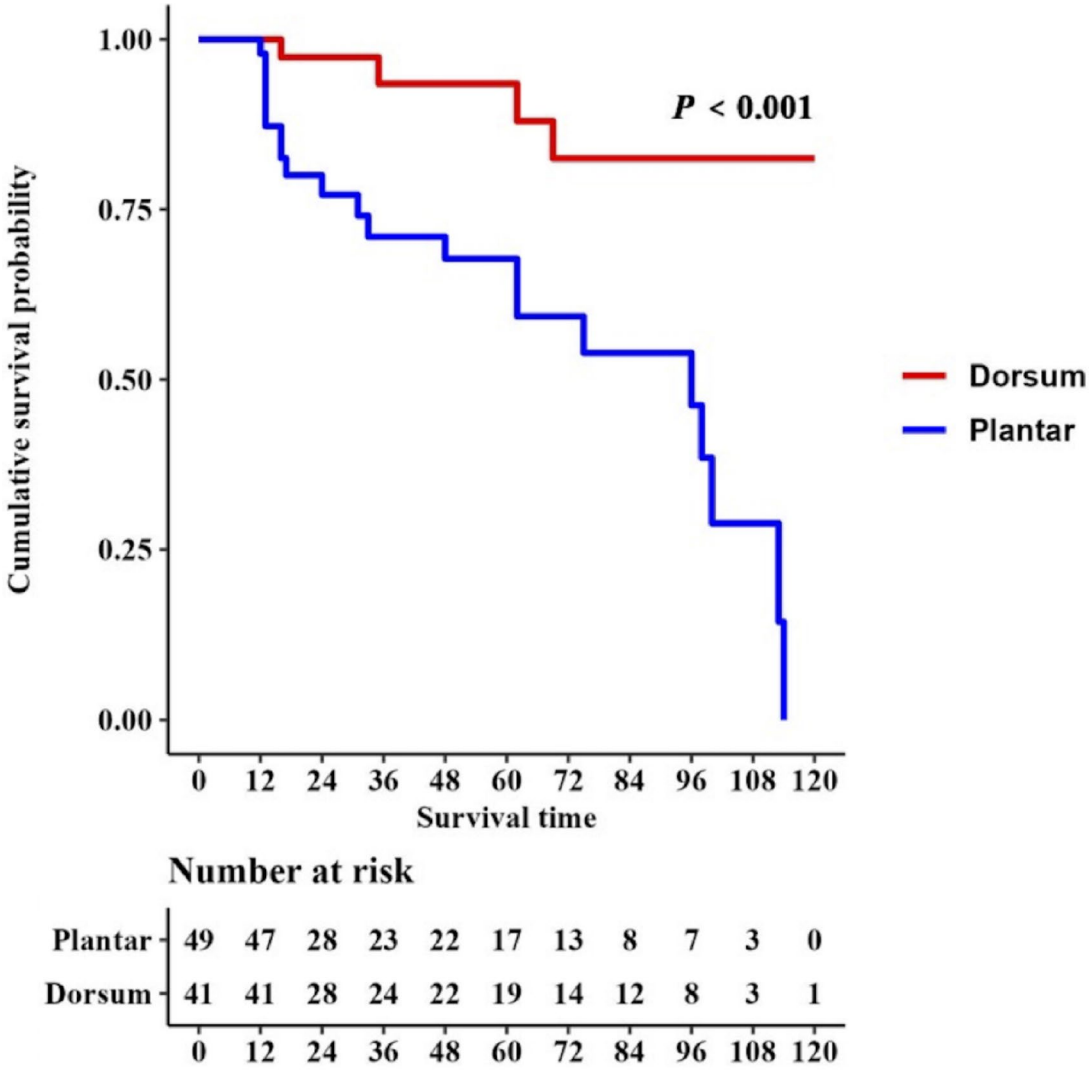


Fig. 3. Kaplan–Meier curves comparing ulceration-free survival between plantar and dorsal flaps. Flaps located in pressure-bearing plantar regions exhibit a continuous decline in ulceration-free survival beginning within the first year, with cumulative survival falling below 50% by 72 months. In contrast, dorsal flaps maintain over 70% ulceration-free survival at 120 months, indicating superior long-term stability (log-rank $p < 0.001$).

Univariate logistic regression analysis identified several factors significantly associated with ulceration. Among etiologic subgroups, diabetes was associated with increased odds of ulceration (odds ratio [OR] 3.043, 95% confidence interval [CI], 0.338–27.409; $p = 0.016$). Comorbid bone abnormalities also showed a significant association (OR 3.222, 95% CI: 1.078–9.634; $p = 0.030$) and chronic renal failure with hemodialysis approached significance (OR 8.727, 95% CI: 0.862–88.316; $p = 0.067$). The flap location has emerged as a strong predictor of ulceration. Compared with flaps located on the dorsum, plantar flaps had significantly higher odds of ulceration (OR 6.937, 95% CI, 2.139–22.498; $p = 0.001$). Subunit analysis revealed that forefoot flaps had a highest risk compared to dorsal flaps (OR 18.500, 95% CI, 4.174–81.987; $p < 0.001$). Further detailed anatomical mapping showed that medial forefoot flaps (OR 12.375, 95% CI: 4.941–21.137; $p < 0.001$) and lateral forefoot flaps (OR 9.250, 95% CI: 1.378–62.094; $p = 0.022$) were particularly vulnerable. In contrast, the midfoot and heel regions did not show significant differences[7].

In multivariable logistic regression, after adjusting for confounding variables, including etiology and comorbidities, flap location on the plantar surface remained independent predictor of ulceration (OR 6.191, 95% CI, 1.597–23.999; $p = 0.008$). Other variables such as flap dimension ($p = 0.533$), PTA ($p = 0.442$), and comorbid bone disease ($p = 0.352$) were not statistically significant in the adjusted model (Table 4).

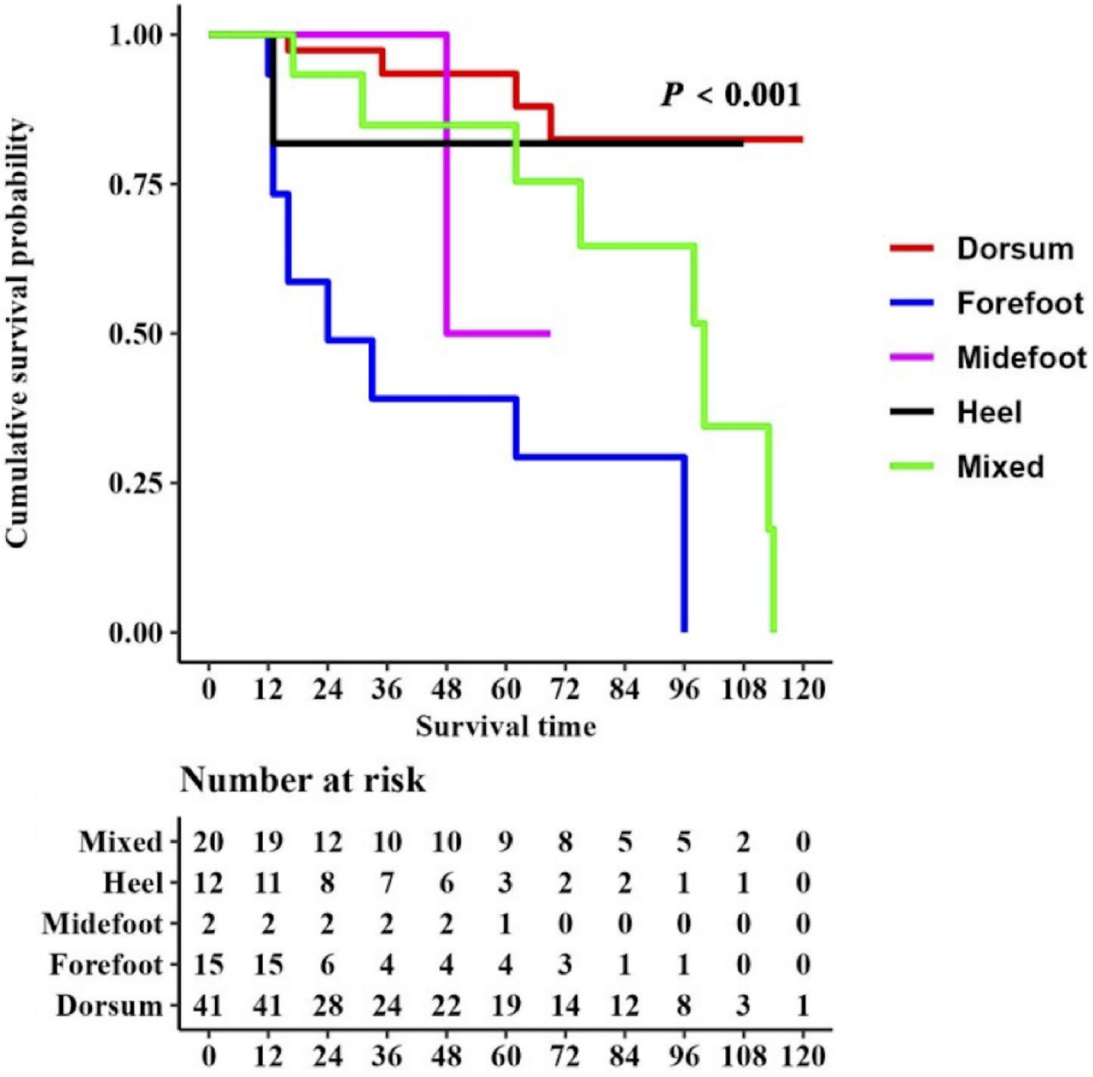


Fig. 4. Kaplan–Meier analysis of ulceration-free survival according to the five-group subunit classification (dorsum, forefoot, midfoot, heel, and mixed regions). Forefoot and midfoot flaps show significantly lower ulceration-free survival rates than heel and dorsal flaps, with most ulceration events occurring within the first 60 months postoperatively (log-rank $p < 0.001$).

Discussion

Free flap reconstruction of the foot is an established approach for limb salvage, aiming not only to achieve durable soft-tissue coverage but also to maintain long-term ambulation and ulcer-free function. Although high flap survival rates have been reported, sustained ulcer-free durability after return to full weight bearing remains a major challenge in foot reconstruction[8,9].

The biomechanical architecture of the foot is complex, involving region-specific loading and shear forces during gait. Accordingly, simple categorization into weight-bearing and non–weight-bearing areas is insufficient for predicting ulceration patterns[7], while the heel has traditionally been regarded as the primary pressure-bearing region, dynamic force transfer during ambulation affects multiple plantar subunits.

Previous studies have predominantly focused on heel reconstruction, reflecting its perceived biomechanical importance; Sayyed et al. reported limb salvage rates of 73.3% in a series of 44 patients with chronic heel ulcers, corresponding to a failure rate of approximately 26.7%, which is comparable to our overall ulceration incidence. Similarly, Matsuda et al. analyzed 42 patients with chronic limb-threatening ischemia and found that approximately half of them experienced ulcer recurrence within five years, with most recurrences occurring within the first two years postoperatively. However, these articles included relatively small patient cohorts and did not systemically evaluate ulceration risk across multiple anatomical subunits.

In contrast, the present study analyzed a consecutive cohort of 90 patients with a minimum two-year follow-up after free flap reconstruction and demonstrated that ulceration occurred significantly more frequently in plantar flaps than in dorsal flaps. Among plantar reconstruction, the forefoot, particularly the medial and lateral subunits, showed the highest ulceration rates. These finding challenges the traditional heel-centric paradigm and suggests that the biomechanical vulnerability after free flap reconstruction extends beyond the heel.

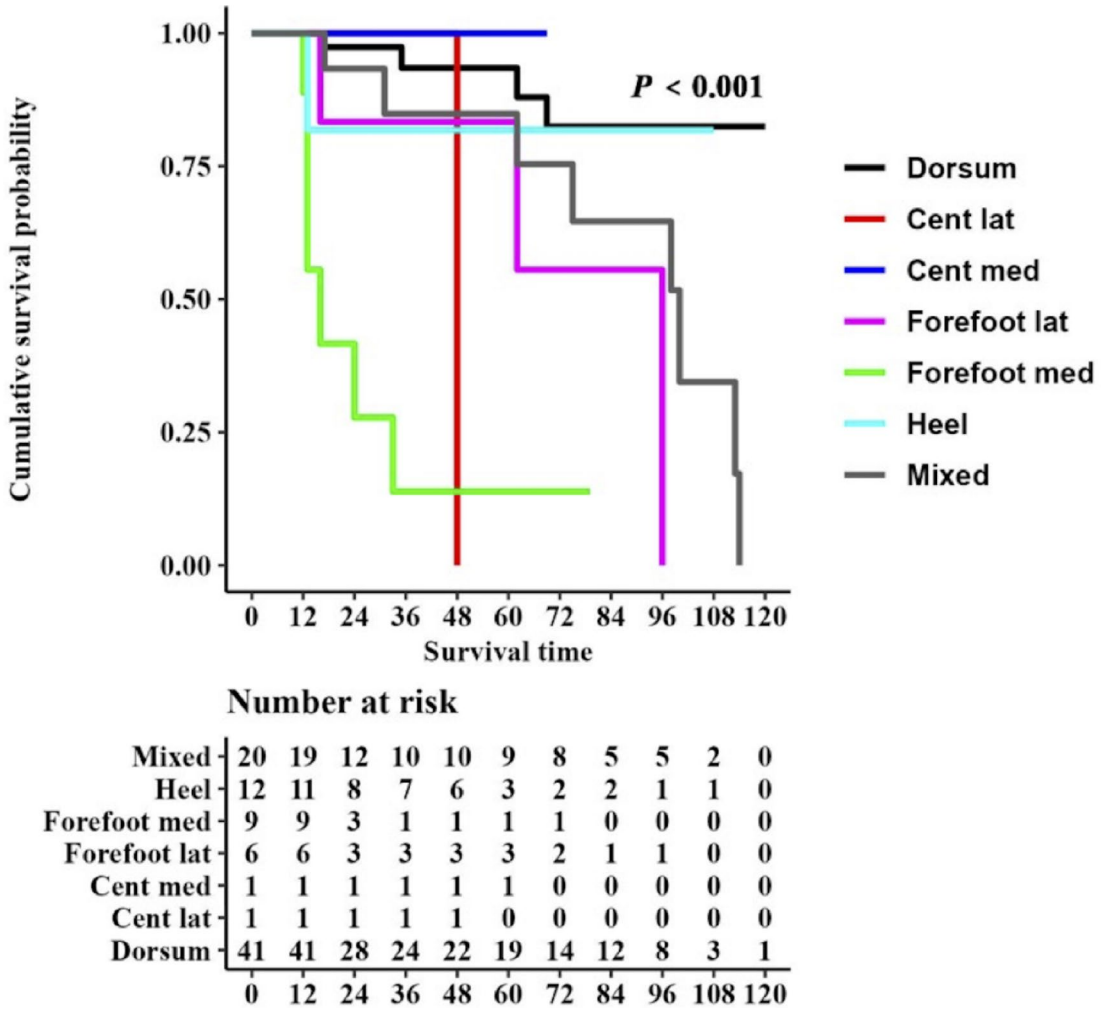


Fig. 5. Kaplan–Meier curves further stratified by detailed anatomical subunits. Forefoot flaps, especially those involving the medial and lateral subunits, demonstrate the earliest and most pronounced decline in ulceration-free survival, with the medial forefoot showing the steepest decrease within the first 24–36 months. Heel and central forefoot flaps present intermediate risk, whereas dorsal flaps demonstrate favorable long-term outcomes (log-rank $p < 0.001$).

While the heel is primarily exposed to vertical loading during initial contact, the forefoot must accommodate both compressive and shear forces during push-off, rendering reconstructed tissue in this region particularly susceptible to mechanical failure. This observation is consistent with biomechanical studies demonstrating peak plantar pressures in the forefoot and hallux regions during gait, especially in the presence of toe deformities[1,3].

We also analyzed the patterns of ulceration between the regions. In our cohort, plantar ulcers typically developed later (mean 8.45 months postoperatively) and were often recurrent and severe, whereas dorsal ulcers appeared earlier (mean 1.25 months), were less severe, and generally resolved with conservative management. This difference suggests that dorsal ulcers are more likely related to shoe friction and adapt over time, whereas plantar ulcers reflect cumulative mechanical failure from repetitive loading. Our Kaplan–Meier analysis further highlighted this distinction, showing a continuous decline in ulceration-free survival for plantar flaps—falling below 50% by 72 months—while dorsal flaps maintained over 70% survival at 120 months. This gradual and ongoing risk pattern differs from prior reports in ischemic cohorts, where ulcer recurrence was concentrated within the early postoperative period, and underscores the need for prolonged surveillance after plantar reconstruction[10].

Multivariate analysis identified plantar flap location as the sole independent predictor of ulceration, even after adjusting for diabetes, bone disease, and other established risk factors. This finding suggests that anatomical location—and the cumulative mechanical environment it represents—may exert a greater influence on long-term flap durability than systemic comorbidities or flap type. Sensory restoration was not specifically evaluated in this study; nerve coaptation or deliberate sensate flap reconstruction was not routinely performed, and objective sensory testing was unavailable for analysis. While impaired sensation, particularly in diabetic patients, is a recognized contributor to ulceration, the present analysis focused on anatomical location as a reproducible determinant of long-term ulcer risk.

	Univariable analysis		Multivariable analysis	
	p-value	OR (95% CI)	*p*-value	OR (95% CI)
Etiology of wounds				
Diabetes	0.016**	3.043 (0.338 ~ 27.409)	0.030*	3.458 (1.127–10.612)
Oncologic	0.136	0.190 (0.021 ~ 1.689)	0.135	0.142 (0.011 ~ 1.837)
Trauma	0.008**	0.235 (0.081 ~ 0.680)	0.163	0.349 (0.079 ~ 1.533)
Chronic renal failure with hemodialysis				
Yes	0.067	8.727 (0.862 ~ 88.316)		
No		Ref.		
Comorbid bone disease	0.036	3.222 (1.078 ~ 9.634)	0.352	1.857 (0.504 ~ 6.848)
Flap location	0.001**			
Dorsum		Ref		Ref
Plantar		6.937 (2.139 ~ 22.498)	0.008**	6.191 (1.59 ~ 22.999)
Flap location				
Dorsum		Ref		
Forefoot	< 0.001	18.500 (4.174 ~ 81.987)		
Midfoot	0.140	9.250 (0.480 ~ 178.072)		
Heel	0.511	1.850 (0.295 ~ 11.596)		
Flap location				
Dorsum		Ref		
Central lateral		Ref		
Central medial	0.452	0.687 (0.258 ~ 1.828)		
Forefoot lateral	0.022**	9.250 (1.378 ~ 62.094)		
Forefoot medial	< 0.001**	12.375 (4.941 ~ 21.137)		
Heel	0.544	1.850 (0.295 ~ 11.597)		
Flap dimension	0.533	1.003 (0.993 ~ 1.013)		
PTA	0.479	1.441 (0.524 ~ 3.966)	0.442	1.555 (0.124 ~ 2.489)

Table 4. Univariable and multivariable analysis of risk factors associated with ulceration.

The high ulceration rates observed in forefoot reconstructions have important clinical implications. Although most patients were able to return to ambulation, those with medial or lateral forefoot flaps required closer postoperative surveillance and, in some cases, secondary surgical intervention for recurrent or severe ulcers. These findings highlight the importance of anatomically informed reconstructive planning and support the use of flap designs that better accommodate the mechanical demands of the forefoot. Recent studies reporting favorable outcomes with thin free perforator flaps for forefoot reconstruction further support this approach[5,7,11].

Several limitations of this study should be acknowledged. The retrospective, single-center design and the heterogeneous nature of the cohort—including diabetic, traumatic, infectious, and oncologic etiologies with varying comorbidities—may introduce confounding despite statistical adjustment and limit generalizability. Detailed biomechanical factors known to influence plantar pressure, such as foot morphology, preexisting deformities, hindfoot alignment, toe contractures, joint stiffness, gait alterations, muscle imbalance, and the use of orthotics or off-loading devices, were managed individually in clinical practice but were not documented in a standardized manner suitable for quantitative analysis. In addition, several clinically relevant factors known to influence plantar pressure and ulcer vulnerability—including flap thickness and secondary debulking, sensory status and the absence of neurotization, the severity of neuropathy, and postoperative measures such as orthotics, custom footwear, and off-loading or rehabilitation—were applied in an individualized manner and could not be consistently quantified for retrospective multivariable modeling. Sensory function was not objectively graded, and nerve coaptation was not routinely performed, limiting assessment of its contribution to ulcer risk. The anatomical subunit classification used in this study provided useful granularity but cannot fully represent the dynamic complexity of gait mechanics or shear forces during propulsion. Sample sizes within certain subunits were modest, which may restrict statistical power for region-specific comparisons. The absence of direct plantar pressure measurements, pedobarographic mapping, or gait analysis also prevented objective correlation between mechanical load distribution and ulcer development.

In summary, our findings highlight the importance of anatomically informed surgical planning and prolonged surveillance, particularly for plantar reconstructions. Future research should focus on developing strategies tailored to the unique mechanical demands of each foot subunit, with emphasis on both early and late postoperative monitoring to optimize outcomes and preserve limb function.

Conclusion

Free flap reconstruction provides reliable coverage and functional restoration for complex foot defects; however, long-term ulceration may still occur despite successful reconstruction. This study demonstrates that long-term ulcer risk after free flap reconstruction is strongly dependent on defect location. Plantar reconstructions,

particularly those involving the forefoot subunits, are associated with a substantially higher propensity for ulceration compared with dorsal reconstructions. These findings underscore the importance of sustained postoperative follow-up to preserve long-term ulcer-free durability after foot reconstruction.

Data availability

The datasets used and analyzed during the current study are available from the corresponding author upon reasonable request.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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