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Soft Tissue Reconstruction of Open Fractures of the Lower Limb: muscle versus fasciocutaneous flaps

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Abstract

Early vascularized soft tissue closure has long been recognized to be essential in achieving eventual infection free union. The question of whether muscle or fasciocutaneous tissue is superior in terms of promoting fracture healing remains unresolved. Here we review the experimental and clinical evidence for the different tissue types and advocate that the biological role of flaps should be included as a key consideration during flap selection.

Introduction

Open tibial fractures are severe injuries, largely affecting young men of working age, and take on average 43 weeks to unite, with 13% developing non-union in the best centres[1]. There is, therefore, an urgent need to enhance the process of bone repair in these patients. There have been numerous innovations in the techniques used for fracture stabilization as well as biological therapy, such as bone morphogenetic proteins (BMPs)[2]. Improvement in the care pathway, through a multidisciplinary and integrated orthoplastic approach, has also led to significant improvements in patient outcomes[3-6]. These refinements have reduced the mean union time to 26 weeks[5].

Considerations when planning soft tissue coverage include the size and location of the defect as well as donor site morbidity. An area which has not featured prominently in determining flap choice thus far is the potential biological role the flap may play in the fracture repair process. However, there is a growing body of experimental evidence that demonstrates that the biological characteristics of the tissues in a flap can significantly influence fracture healing, thereby potentially reducing union time and the rate of delayed or non-union.

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Experimental Evidence

Wound healing properties of soft tissue flaps

The role of soft tissue reconstruction in open fractures is not limited to wound coverage to prevent wound desiccation and infection. Soft tissues also contribute to fracture repair by serving as a local source of stem or osteoprogenitor cells, growth factors and vascular supply[7-10].

Vascular Supply

A key role of soft tissue flaps in lower limb trauma is to serve as source of vascular supply to bone ends that have been stripped of periosteum and undergone disruption of the endosteum[11]. There is evidence that muscle contributes greater vascularity to a defect than fasciocutaneous tissue[12-16]. A study using a canine model to compare the blood flow at the musculocutaneous and fasciocutaneous flap/wound interfaces with no underlying fracture showed that whilst there was an initial increase in muscle blood flow in the first 24 hours, the deep surface of the fasciocutaneous flap underwent a slower and steadier increase in blood flow over the experimental period of 6 days to exceed that of muscle by this time point[17], yet there was greater evidence of healing in the muscle group [18]. Using a murine tibial fracture model, Harry et al. found that at all time points the vascular density was greater in fasciocutaneous tissue in apposition with a periosteally stripped fracture than muscle, and in spite of this, fracture repair was more rapid in the muscle group[19, 20]. These observations suggest that while vascularity is essential for wound healing, including bone repair, other biological factors become limiting, once an adequate blood supply threshold has been met.

Cellular contribution

Fracture repair requires the recruitment of osteoprogenitor cells. Mesenchymal stem cells (MSCs) are, by definition, multipotent and can therefore serve as a source of osteoprogenitor cells. MSCs may originate from a variety of tissues including the bone marrow, periosteum, dermis, adipose tissue and muscle, as well as blood vessels and the circulation. In closed fractures, the main sources of osteoprogenitor cells are thought to be the bone marrow and periosteum[21-25]. However, high energy open fractures of long bones are characterized by loss of the periosteum and bone marrow, especially following insertion of an intramedullary rod. Under these circumstances the main osteoprogenitor cells must originate from the local soft tissues or the circulation[10, 26].

It is well established that muscle provides a suitable environment for osteogenesis, although damaged muscle is less effective[27]. In 1965, Urist[28] found that new bone formed readily when decalcified bone was implanted into muscle and deduced that the inductor cells were derived from the host bed. Furthermore, purified BMPs injected into muscle are capable of inducing ectopic bone formation[29, 30]. Using a mouse model, Zacks et al.[31] found that muscle (but not liver tissue) demonstrated a significant osteogenic effect. Extraskeletal ossification observed in patients with fibrodysplasia ossificans progressiva[32] and heterotopic ossification following either orthopaedic surgery or blast injuries tend to occur in muscle[33, 34].

Both fasciocutaneous tissue and muscle are rich reservoirs of MSCs[9, 10]. However, the characteristics, including the osteogenic potential, of MSCs vary depending on their tissue origin. For example, human stromal cells derived from muscle exhibit a significantly greater potential for osteogenesis than those from fasiocutaneous tissue, including both skin and adipose, and are equivalent to those from bone marrow[35]. Using a critical sized rat femoral diaphyseal defect model, muscle was found to be more effective in promoting bone repair than adipose tissue[36]. Muscle-derived stem cells can be recruited from muscle and stimulated to undergo osteogenic differentiation by proinflammatory cytokines, especially TNF-α, released at the site of injury[35].

Cytokine/ growth factor environment

Muscle also provides a bone anabolic environment through the expression of members of the transforming growth factor-β (TGF-β) superfamily of growth and differentiation factors, including the BMPs. The reciprocal relationship between muscle and bone mass is well described, particularly the strong association between sarcopenia (age-related loss of muscle mass) and osteopenia. Muscle and bone are believed to be mutually regulating via physical forces and cytokine control. Indeed, recent evidence indicates that muscle serves as an endocrine organ that releases trophic factors, known as myokines, which have been identified as key regulators of the muscle and bone mass. Further observations suggest that intact muscle supports bone repair via the release of bone anabolics, including IGF-1, IL-6, BDNF and FGF-2[37-39] while severely injured muscle, such as following military trauma, impairs this process through the release catabolic myokines, including myostatin (GDF-8) [40-42]. Therefore, the net effect on bone is dependent on the balance of these factors.

Anti-microbial property

Soft tissue flaps are believed to possess an anti-bacterial property that is independent of vascularity. Chang and Mathes used a canine model to compare the anti-microbial properties of different tissues during wound healing[43]. Chambers inoculated with bacteria were inserted beneath random pattern flaps raised on the flanks with no underlying fracture. Muscle was found to be superior in eliminating bacteria from the wound bed. In a separate study, they compared bacterial growth within the wound fluid at interface of musculocutaneous and fasciocutaneous flaps and found that despite a higher blood flow and tissue oxygen tension in the fasciocutaneous group, muscle exhibited a greater ability to reduce the bacterial count[17, 18]. Moreover, histological examination revealed greater evidence of wound repair, including increased collagen deposition, at the muscle interface[18].

Comparison in animal models of bone repair

Recent evidence suggests that the presence of muscle is an important contributor to bone healing[9, 10, 44]. For example, the size of fracture callus is greater adjacent to muscle[45] and muscle coverage accelerates fracture repair in murine models[19, 46].

Schemitsch et al.[11, 47-50] compared cutaneous and muscle tissues in a series of studies using a canine open tibial fracture model. A devascularized segment of tibia was covered with either transposed tibialis muscle and the skin incision closed (muscle flap group) or skin closed directly following excision of the underlying fascia (skin group), and fracture healing was assessed. There was a significant increase in the bone blood flow and rate of union in the muscle flap group compared to the skin group[11, 48]. Muscle flaps were also found to significantly increase cortical porosity, enveloping callus and intracortical new bone formation[49]. Notably, there was no direct correlation between the soft tissue blood flow and the indices of bone repair, and resting muscle blood flow was found to be higher in the control limb using the microsphere technique[47]. Subsequent investigation of flap perfusion showed no difference in extraosseous soft tissue perfusion at the fracture site between the different groups[50]. However, this model does not emulate the clinical scenario as fascia beneath the anterior skin was excised in both groups, and only one-third of the circumference of the osteotomised tibial segment was in contact with the soft tissue flap, with the posterior segment in direct apposition with intact periosteum and musculature in both groups.

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Our group developed a murine tibial fracture model to emulate the high-energy injuries encountered in clinical practice. One third of the circumference of the fracture was permitted direct contact with either muscle of fasciocutaneous tissue by excluding the remainder with polytetrafluoroethylene[19]. At 28 days following fracture, there was greater healing in the experimental muscle coverage group compared to skin and fascia alone with almost 50% more mineralized bone content and a three-fold stronger union in the muscle group compared to fasciocutaneous group despite a higher vascular density in the fasciocutaneous tissue compared to the muscle at all time points[19, 20].

In a series of studies, Utvag et al.[27, 46, 51, 52] examined the effect of separating muscle from the fracture site in the long bones of the lower limb in rodents. Interposition of an impermeable membrane between periosteum and muscle resulted in impaired healing in a rat femoral model[51]. However, a delay of 2 weeks in insertion of the impermeable membrane did not have any detrimental effect, indicating that early direct contact of muscle with the fracture site enhances fracture healing[52]. Excision of the anterolateral compartment muscles in a rat tibial fracture model also resulted in delayed healing. This effect was abolished when the muscle defect was corrected by transposition of the gluteal muscle[46]. Furthermore, isolating a tibial fracture in a rat model with nitrocellulose membranes with pore sizes ranging from 3 to 50kDa still resulted in impaired healing, confirming that direct contact of muscle with the fracture site, likely the cellular component, is an important factor in the healing of diaphyseal fractures[53].

Clinical Evidence

Most of the relevant clinical evidence comprises descriptive retrospective observational case series (Table 1) and all studies are categorized as Level 4 evidence according to the Oxford Centre for Evidence-based Medicine. Few of these specifically compared muscle with fasciocutaneous flaps and those that did were severely limited by the lack of power and case heterogeneity, including a wide variety of patients with clinical indications ranging from open fractures to burns or contour deficits. There were insufficient details in the publications to allow us to separate the flaps used to cover open fractures. Furthermore, the outcome measures differed considerably between studies, for example, not all studies reported time to fracture union, rates of deep infection or even flap survival. Therefore, the currently the published literature precludes amalgamation of data from different studies and hence any meaningful meta-analysis or systematic review that can provide guidance for the use of different flap options in the management of open fractures of the lower limb.

Muscle flaps

It has been observed that open fractures of bones not surrounded by muscle, such as the tibia, unite slowly[54] and that healing of open bone defects is accelerated when a muscle flap is used to cover the wound. Furthermore, intact muscle appears to be more effective at promoting bone repair than injured muscle[55]. In a retrospective review of 84 consecutive patients with severe open tibial fractures, which included 79 grade IIIB and five Gustilo grade IIIC fractures, Gopal et al. presented their ‘fix and flap’ approach comprising early effective debridement, skeletal stabilization and subsequent obliteration of the dead space with a well-vascularized muscle flap[55]. Their longer-term outcome of 34 severe open tibial fractures, including 30 graded as Gustilo grade IIIB, showed a mean union time of 41 weeks, and rates of limb salvage and amputation compared favourably with other series[56].

Other authors have also commented that muscle provides superior coverage of open tibial fractures[55, 57-60]. Georgiadis et al.[59] highlighted the ability of muscle flaps to reduce both healing time and deep infection while Small and Mollan[61] retrospectively reviewed 168 open tibial fractures treated over a 15-year period and found a lower necrosis rate in

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local muscle flaps (13.3%) and free tissue transfer (most were muscle only latissimus dorsi and rectus abdominis flaps; 10%) compared to fasciocutaneous flaps (21.2%).

Fasciocutaneous flaps

Fasciocutaneous flaps are popular and have been used successfully in large clinical series to reconstruct open tibial defects[62-68]. Local fasciocutaneous flaps are reliable for lower limb reconstruction, as demonstrated by Ponten[69] in his study of 23 cases. They offered significant advantages, including simplicity, availability and versatility, replacing 'like with like' without sacrificing muscle function[62, 63, 65, 70]. However, in a series of 100 consecutive local fasciocutaneous flaps, which included 67 to the lower extremity, Hallock[62] reported that 15% required further surgical intervention, with the majority in lower limb wounds and attributed to peripheral vascular insufficiency. Although the majority of patients requiring vascularized tissue had been subject to trauma, it was not clear that all patients had fractures. The coverage of contaminated wounds was highlighted, with short-term healing achieved, suggesting that local fasciocutaneous flaps could be used to cover previously infected fractures[18].

The major advantage of local fasciocutaneous flaps is their relative simplicity of procedure. However, in patients with high-energy injuries, they may be susceptible to tip necrosis. Erdmann et al.[64] published their experience of pedicled fasciocutaneous flaps in lower limb trauma. Over a five-year period, they used distally-based, islanded fasciocutaneous flaps to reconstruct open tibial fractures to cover the distal one-third of the leg, ankle, heel or foot in 61 patients, with 25 fractures graded as Gustilo IIIB. The overall complication rate was 7.6%, which included five patients with Gustilo IIIB fractures suffering complete flap loss and four patients developing chronic osteomyelitis that led to non-union. Thus, the complication rate for coverage of Gustio IIIB fractures with distally-based islanded fasciocutaneous flaps reached 20%. The mean time to fracture healing was 5.9 months. In a prospective multicentre study involving high energy lower limb trauma, rotational flaps, including fasciocutaneous tissue and muscle, were compared to free muscle flaps in 195 limbs in 190 patients[60]. In patients with the most severe grade of osseous injury, wound complications including infection, necrosis or flap loss, were significantly higher in the rotational flap group (44% compared to 23%), and furthermore, these were 4.3 times more likely to require operative intervention.

Fasciocutaneous flaps have been found to be useful in chronic osteomyelitis of the lower limb by Hong et al.[67]. Over a three-year period, they treated 28 consecutive patients with surgical debridement and reconstruction using free anterolateral thigh perforator flaps, although six of these fasciocutaneous flaps were combined with a segment of vastus lateralis muscle. The well-contoured soft tissue flaps allowed effective resurfacing at the level of the ankle, permitting normal footwear, and unlike the muscle flaps, the elasticity of the skin flaps permitted easy re-exploration for secondary bone grafting procedures, with tension-free closure. Although lacking long-term follow-up, they felt that with adequate debridement and obliteration of dead space, the anterolateral thigh perforator flap was a time-efficient, functional, aesthetic and safe procedure that provided successful coverage for chronic infection.

More recently, the sural artery flap has gained popularity. However, in a multicentre review of 70 flaps, Baumeister et al.[71], found that up to 36% developed necrosis, and this was most likely to occur in patients with comorbidities, including diabetes mellitus, venous insufficiency and peripheral arterial disease. This is the sub group that is erroneously considered by some surgeons to be unsuitable for free flaps.

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Studies comparing fasciocutaneous and muscle flaps

In a retrospective review over an 18-year period, Hallock assessed the role of muscle and fascia flaps in lower extremity trauma[65]. Details of flap coverage in 160 limbs in 155 patients, of which 60 were local muscle, 50 local fascial and 74 free muscle and fascial flaps, were reported. Flap selection was not randomly assigned, but based on clinical need. Complications were related to the severity of the injury, with 39% associated with free flap transfer, whereas local muscle and local fascia flaps had similar morbidities of 27% and 30%, respectively.

Donor site morbidity is often a factor in flap selection. In a retrospective review, the same author compared the relative donor site morbidity of muscle and fascial flaps[63]. In total, 147 local muscle/musculocutaneous and 122 fascia/fasciocutaneous flaps were used to reconstruct all regions of the body. These included a total of 45 muscle and 72 fasciocutaneous flaps for the lower limb, although it was not clear whether all these patients had exposed fractures. Overall, donor site complications were equivalent at 14% for each group while major complications, including nerve injury, failed graft, necrosis or ulceration, were infrequent in both. Most difficulties, however, were encountered below the knee with fasciocutaneous flap donor sites, where no local muscle option was available, and the skin grafted donor sites were described as cosmetically unappealing.

Finally, a retrospective review of patients with open tibial fractures treated with either free muscle or facsciocutaneous flaps showed that similar numbers went on to achieve bony union and were able to walk unaided at two years[72]. The authors found that muscle conformed better to complex defects but fasciocutaneous flaps better tolerated secondary surgical procedures.

Clinical Implications

Meticulous wound debridement removes any non-viable soft tissue including muscle that may serve as a nidus of infection and a source of catabolic myokines to inhibit bone repair. From the available data and our own experience, we suggest that fasciocutaneous flaps may be superior to muscle for coverage of rapidly uniting metaphyseal fractures, particularly around the ankle, thereby avoiding skin grafts, which might be susceptible to minor trauma. However, muscle in direct apposition with diaphyseal fractures would aid healing. While muscle flaps covered with skin grafts are aesthetically unappealing and can be difficult to elevate for secondary procedures such as bone grafting, an alternative which retains the biological benefits of muscle apposition is to use chimeric flaps, such as a free anterolateral thigh flap that includes a segment of vastus lateralis[73] (Fig. 1). The plasticity of muscle also helps to obliterate the dead space, thereby reducing potential complications associated with hematoma formation[74]. In summary, thorough wound debridement and early flap coverage of open fractures achieves infection-free union and the biological contribution of the constituent tissues should be taken into consideration during flap selection.

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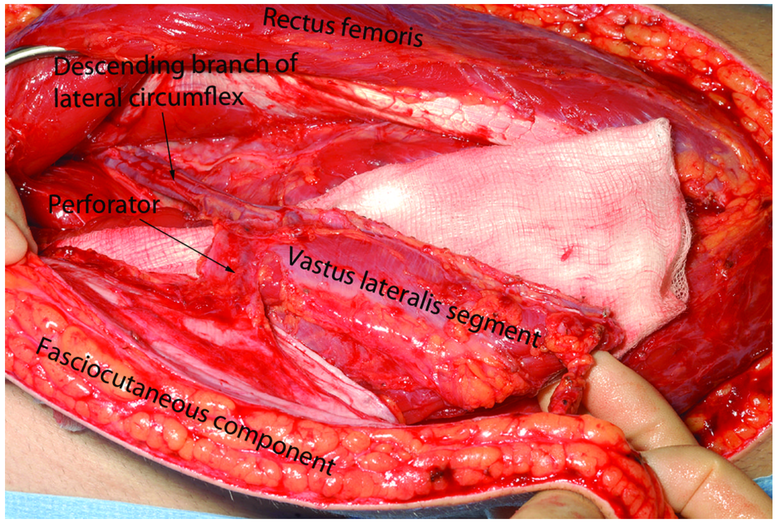

Figure 1.
Chimeric free ALT flap, with a segment of vastus lateralis

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Table 1

Evidence base for soft tissue coverage of open fractures of the lower limb

Authors	Study design	Study groups	Flaps	Outcomes	Comments
Yazar et al 2006 [72]	Retrospective observational study	174 patients, 177 free flaps distal 1/3rd tibia and ankle fractures (segmental bone defects and vascularized bone grafts excluded) Mean age: 35.4 years Follow-up time: 2 years	Group I: 98 free muscle flaps Group II: 79 free fasciocutaneous flaps Flap selection not randomised Muscle flaps used for large wounds FC flaps for shallow defects Mean number of previous debridement procedures 3-4	Complete flap survival: Group I: 92.9%, Group II: 91.1% Post-op infection: Group I: 11.2%, Group II: 12.7% Primary fracture union: Group I: 84.5%, Group II: 81% Time to union not available Unaided walking at 2 years" Group I: 95.8%, 98.7%	Outcomes for free muscle v FC flaps in severe lower limb trauma are equivalent.
Hong et al 2005 [67]	Retrospective observational study	28 patients with chronic osteomyelitis of lower limb Mean age: 42.8 years Mean follow-up: 18.2 months	All ALT flaps (6 included vastuslateralis muscle)	All flaps survived All achieved acceptable gait function No recurrence or persistence of osteomyelitis 2 flaps had partial wound dehiscence which healed spontaneously (both diabetic)	Excellent success rate with free ALT flap. No comparison between FC alone and chimeric flaps..
Van Landuyt et al 2005 [68]	Retrospective observational study	25 patients, 28 flaps; Mixed indications including trauma, burns, amputation Mean age: 37.6 years Mean follow-up time: not available	All DIEP flaps 5 flaps for open lower limb fractures	Complications in 60% including wound dehiscence & partial necrosis	Heterogeneous cohort, low numbers. Apparent high complication rate with free DIEP flaps for open leg fractures.
Hallock 2004 [66]	Retrospective observational study	19 patients, 20 flaps 14/19 trauma-related Mean age: not available Mean follow-up: not available	FC perforator flaps: Pedicled (5/20) or free (15/20), 7 chimeric flaps including gracilis muscle Flap selection not randomised 45% for foot and ankle defects, all free flaps	6/20 pedicled flaps: 1 partial necrosis, 1 cellulitis and 1 heel pressure sore 15/20 free flaps successful but 2 had venous thrombosis (salvaged); 1 partial necrosis 2 anastomotic thrombosis (information of flap fate unavailable)	Small series, high complication rate in local compared to free flaps. No comparison between FC only and chimeric flaps.
Baumeister et al 2003 [71]	Retrospective multi-center observational study	67 patients, 70 flaps Mixed indications: 13 acute defects (11 trauma, 2 tumor resection); 36 longstanding post-traumatic defects or unstable scars, 15 chronic ulcers, 6 pressure sores Mean age: 54.1 years Mean follow-up time: not available	All pedicledsural artery FC flaps	Overall complicaton rate 59% • Partial or tip necrosis 12/70 (17.1%) • Complete necrosis 13/70 (18.6%) • Infection 5/70 • Haematoma 2/70 • Unresolved osteomyelitis 2/70	Pedicledsural artery FC flaps associated with high complication rates especially in older age groups and those with comorbidities.

Authors	Study design	Study groups	Flaps	Outcomes	Comments
				• Delayed healing 4/70 • Donor-site complications 3/70 Age and flap necrosis rate (partial and complete): • 21-40 years - 0/16 flaps • 41-50 years - 5/11 (45%) • 51-60 years - 8/14 (57%) • 61-70 years - 7/16 (44%) Comorbidity and flap necrosis rate (partial and complete): • Healthy (no comorbidity) - 3/28 (11%) • One disease (venous insufficiency, peripheral arterial disease or diabetes mellitus) 9/15 (60%) • 2 diseases 6/12 (50%) • 3 diseases 3/3 (100%) • Other systemic disease: 4/12 (33%) • Venous insufficiency 10/16 (63%) • Peripheral arterial disease 9/13 (69%) • Diabetes Mellitus 11/19 (58%) • Osteomyelitis 1/6 (17%)	
Pollak et al 2000 [60]	Prospective multicentre observational study	601 patients enrolled: 190 patients, 195 limbs requiring flap coverage Mean age: 36 years Follow-up time: 6 months	Rotational flap: 88 limbs Free flap: 107 limbs Rotation flap group comprised 26 FC and 62 muscle flaps - but no comparison made between groups Free flaps: 95.3% muscle, remainder 'other'	Overall 27% complication rate, 87% of which required further operative treatment; Flap loss rate equivalent in rotational (8.0%) and free flap groups (8.4%). Among patients with most severe osseous injury, 44% rotational flap group v 23% free flap group had wound complications. Rotational flap group was 4.3 fold more likely to have wound complication requiring operative intervention compared to free flap group	Free flaps - lower complication rate than local flaps (muscle or FC) when used to cover severe open fractures.

Authors	Study design	Study groups	Flaps	Outcomes	Comments
Gopal et al 2000 [55]	Retrospective observational study	80 patients, 84 fractures All GustiloIIIb or IIIc open tibial fractures Mean age: 37 years Mean follow-up: min 1 year, until bony union	All muscle flaps: 9 pedicled, 75 free 63/84 within 72 hours, 21/84 delayed Flap selection not randomised	Limb salvage 95% Primary bone union 66% Mean fracture union time 41 weeks Flap failure (requiring further surgery) 3.5% Deep fracture site infection 9.5% but at final review, all patients infection free and ambulant	Combined early orthoplastic approach comprising debridement, fixation and early soft tissue cover with muscle flaps are associated with optimal outcome and reduced complications.
Gopal et al 2004 [56] (follow up of cohort published in 2000 [55])	Retrospective observational study	33 patients, 34 Gustilo type IIIb and IIIc fractures Mean age: 48 years Mean follow-up time 46 months	Orthoplastic approach: • radical debridement • immediate skeletal stabilisation • early soft tissue cover with muscle flap (free or rotational)	Mean fracture union time 41 weeks 34% required further surgery to achieve union 2 patients developed deep infection that resolved Immediate flap cover associated with improved union and infection rates 100% patient satisfaction 41% returned to work SF-36 scores (mental and physical health) comparable with previous studies	Orthoplastic, protocol-driven approach with early muscle flap coverage associated with satisfactory outcome in severe lower limb trauma. No comparison between free or local muscle flaps.
Hallock 2000 [65]	Retrospective observational study	155 patients, 160 limbs, 184 flaps Indication: soft tissue closure for lower limb trauma but not all patients had open fractures 10 limbs Gustilo type IIIc fractures Mean age: not available Mean follow-up: 2 years	Local muscle: 60 Local FC 50 (5 distally-based) flaps Free muscle: 61 Free fascial: 13 Flap selection not randomised	91% of limbs salvaged Overall, 33% all flaps had complications, more likely in more severe injuries Complications (i.e. requiring additional surgery, complete flap failure, inability to achieve intended purpose, or significant morbodity to injured limb): Free flaps 39%, local muscle 27%, local fascia 30% 6/10 Gustilo type IIIc had complications : • 8 required free flaps, 2 required amputations • 4 limbs salvaged ’without any adverse sequelae’ Early soft tissue closure reduced risk of complications: Acute 19%, subacute 46%, chronic 45% Local FC flaps less reliable than local muscle flaps during acute period: 23% v 11% complication rate 5 distal-based local FC flaps used: 1 total necrosis due to venous congestion.	Early closure is associated with lower complication rate. Free flaps are used for large and severe wounds. Local flaps are an alternative for limited defects, but higher complication rates with local fascial flaps compared to local muscle flaps.
Erdmann et al 1997 [64]	Retrospective observational study	61 patients, 66 flaps Acute trauma fractures: 80.3% Mean age: 50.5 years	All distally-based islanded FC flaps: Distal 1/3rd leg: 71.2% 48/61 (78.7%) had associated fractures; 25 were	Mean time to fracture union 5.9 months (2-18 months) 6/66 (9.8%) patients developed non-union requiring bone grafting	Distally based islanded FC flaps for covering severe

Authors	Study design	Study groups	Flaps	Outcomes	Comments
		Mean follow-up time 13 months	Gustilo type IIIb fractures Flap procedures within 72h: 78.8%	Loss of flap requiring further surgery in 5/66 (7.6%) All 5 patients sustained Gustilo type IIIb fractures and were heavy smokers. Tip necrosis in 6/66 (9.1%)	open fractures are associated with relatively high flap failure rates (16.7%).
Hallock 1993 [63]	Retrospective observational study	269 flaps Mixed indications and sites 117 below knee Age: from <20 to >70 years Follow-up time: not available	All local flaps: • 147 muscle/ musculocutaneous flaps • 122 fascia/FC flaps Below knee: • 42 muscle • 3 musculocutaneous • 72 FC Flap selection not randomised	Overall donor site complication rate 14% (same for both groups) Most frequent donor site problem in FC flaps was SSG 'take' 73% v 16% in muscle group Major complication rate (i.e. requiring second operation to donor site e.g. further flap or SSG): 3% both groups 50% of major complications occurred below the knee: muscle: 5/42 (11.9%), FC: 9/72 (12.5%) Flap complications: muscle: major 4/42 (9.5%), minor 4/42 FC: major 10/72 (13.9%), minor 7/72 (9.7%) (Minor complications included seromas, minor wound dehiscence, epidermolysis, wound infections)	Higher rate of major complications in FC (13.9%) compared to muscle flaps (9.5%).
Georgiadis et al 1993 [59]	Retrospective observational study	55 patients Gustilo type IIIb or IIIc fracturesnecessitating free tissue transfer or amputation Mean age: 32.5 years Mean follow-up: 40 months	Group I: free tissue cover (latissmusdorsi, rectus abdominis, tensor fascia lata) 27 patients •Mean time to soft tissue cover: 21 days Group II: early amputation 18 patients • 2/18 primary closure • 16/18 delayed closure achieved in different ways including 2 free flaps • Mean time to amputation: 5 days	Group I: 81.5% (22/27) successfully salvaged and 96% after 2nd attempt Overall complication rate: 89% • osteomyelitis 56% • 19% required secondary amputation • 19% partial flap loss • 15% complete flap loss • 4% non-union Group II: • 4 stump infections • 13/18 pain in residual limb	No comparison on outcome relating to flap types. Early amputation for unsalvageable limbs leads to good outcomes
Small and Mollan 1992 [61]	Retrospective observational study	165 patients, 168 open tibial fractures Mean age: 24 years Follow-up time: not available	174 flaps in 133 fractures: • local muscle 60 • local FC 33 • local random skin flap 4 • free flap (FC/muscle/bone)70 • cross-leg flap 7	Flap necrosis (partial and complete): • local muscle 8/60 (13.3%); • local FC - 7/33 (21.2%) • free 7/70 (10%) 18 of 22 failed flaps underwent further flap 15/22 (68.2%) SSGs: long term problems including unstable skin with ulceration, chronic bone	Local FC flaps are unreliable for early coverage in severel lower limb trauma; local muscle flaps have a lower complication rate but free muscle flaps are superior.

Authors	Study design	Study groups	Flaps	Outcomes	Comments
			SSG only in 22 fractures primary amputationin 13 fractures Delay to soft tissue cover: 4 days to 2.8 months Flap selection not randomised	infection and non-union	SSG alone is inadequate for coverage of open fractures.
Fischer et al 1991 [58]	Retrospective observational study	43 patients Gustilo type IIIb fractures Mean age: 32 years Mean follow-up time: 104 weeks	All muscle flaps (local 12 and free 12): • 11 patients with early muscle flap (1-10 days) • 19 heal secondary intention • 13 delayed flap cover (11 days to months) Flap selection not randomised	Flap survival: • Free flaps - failure in 2/12(17%) • Rotational flaps - partial slough in 2/12 (17%) Rates of deep infection; chronic osteomyelitis: • secondary healing 10/19 (52.6%); 1/19 (5.3%) • early muscle flap 2/11 (18.2%); 1/11 (9.1%) • delayed flap cover 9/13 (69.2%); 4/13 (30.8%) Bone grafting after soft tissue healing was associated with lower rate of deep infection (31% v 73%), chronic osteomyelitis (0% v 26.7%) and shorter time to fracture union (54 v 63 weeks)	Early muscle coverage is associated with lower infection rates.
Hallock 1991 [62]	Retrospective observational study	100 flaps Mixed indications and sites: 67 lower extremity 54% all cases - trauma Mean age: not available Mean follow-up time: not available	All local FC flaps	97% success - i.e. ultimate wound healing and limb preservation Overall complication rate 26%. 15% all cases required further surgical procedures Higher complication rate for lower extremity and trauma (27.8% total or partial necrosis rate) 63.6% in older patients with peripheral vascular insufficiency Timing: early coverage - 5.6% complication rate subacute 38.5% chronic 36% 37.5% of distal-based flaps had complications	Local FC flaps for open tibial fractures had high failure rate. Early coverage is associated improved outcomes.
Ponten 1981 [69]	Retrospective observational study	22 patients, 23 flaps Mixed indications including unhealed, recent/old fractures, pseudoarthrosis, osteomyelitis, carcinoma Mean age: 42 years Follow-up time: not available	All local FC flaps	3/23 fair (i.e. flap tip loss) 3/23 failures: • 1 50% flap loss requiring further surgery • 1 partial flap loss due to underlying bone infection • 1 flap dislodged	Not possible to segregate the flaps in acute open fractures only. Although local FC flaps are simpler and quicker, they are associated with a high flap loss (partial or

Authors	Study design	Study groups	Flaps	Outcomes	Comments
					complete) of 26.1% in this series of mixed indications.
Byrd et al 1981 [57]	Prospective observational study	18 patients, 20 Gustilo type IIIb fractures Mean age: 30.4 years Follow-up times: 1-34 months	Orthoplastic approach: •early debridement •local muscle or myocutaneous flaps or free myocutaneous flaps within 5 days of injury •external fixation	All fractures united (mean 4 months) Soft tissues stable in all patients Overall complication rate 5% (1 delayed union, 1 necrotising fasciitis following shot gun wound)	Orthoplastic, protocol-driven approach with early debridement and soft tissue cover leads to favourable outcomes and low complication rates. No comparison of different flap types.

FC = fasciocutaneous

SSG = split skin graft