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Review

Free flaps for lower limb soft tissue reconstruction in children: Systematic review☆

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KEYWORDS
Lower limb;
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Abstract *Background:* Since the first reports on microsurgery in children, there has been an evolution in the reconstruction of soft tissue defects as evidenced by a shift to free flaps as the first-line treatment.
Methods: The primary objective of this systematic review was to compare the complication rate of free perforator/fasciocutaneous flaps with free muscular/myocutaneous flaps in pediatric lower limb soft tissue reconstructions. The secondary objective was to evaluate the frequency and severity of complications for both reconstructive options.
A search was performed in the databases PubMed, Web of Science, Embase, Scopus, and Cochrane Library depending on predefined inclusion criteria.
Results: The evolution to perforator flaps from muscular and myocutaneous flaps is reflected in this systematic review as demonstrated by the anterolateral thigh (ALT) flap, which is the most common reconstructive option with a very low complication rate (11.3%) and flap loss. The latissimus dorsi (LD) flap was the second most frequently reported reconstruction with a complication rate comparable with that of the thoracodorsal artery perforator (TDAP) flap (32% vs. 39%, respectively), but the former suffers few failures. The radial forearm (RFA) fasciocutaneous flap can be considered a good alternative for ALT and TDAP flaps with a very low complication rate (16%) and no flap loss.

Abbreviations: ALT, Anterolateral thigh; *DIEAP*, Deep inferior epigastric artery perforator; *RFA*, Free radial forearm; *LD*, Latissimus dorsi; *MVA*, Motor vehicle accident; *PAP*, Profunda artery perforator; *RA*, Rectus abdominis; *SCIAP flap*, Superficial circumflex iliac artery perforator flap; *SIEAP*, Superficial inferior epigastric artery perforator; *STG*, Split-thickness skin graft; *TDAP*, Thoracodorsal artery perforator flap.

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Conclusions: The ALT flap is considered the best reconstructive method for pediatric lower limb soft tissue defects. More adequate prospective studies specifically concerning free flap reconstructions for lower limb defects in children are necessary in the future to provide guidelines for treatment and optimize outcomes in the long term.

Contents

Introduction

Rationale

Mowing accidents are the most frequently reported causes of extensive lower limb trauma in children. In the United States, 9400 children are treated yearly with injuries related to lawn mowers; 37% of these injuries involve the lower extremity, feet, and toes[2]. Motor vehicle accidents (MVA) are also a major cause of lower extremity injuries.[3]

Traditionally, the reconstructive ladder for soft tissue defects of the extremities was a useful guide to reconstruction, but the evolution of microsurgery and increased knowledge of anatomy have made free flaps easier to approach with very high success rates of more than 95% to even 100%.[4-16] The first reports concerning microsurgery in children were in the mid-1970s.[17,18] Currently, free flaps are often regarded as the primary choice for complex soft tissue defects.[19,20] The foot and ankle are not usually amenable to reconstruction with skin grafts or local flaps because of the need for weight bearing and free movement of joints/tendons, respectively. Van Landuyt et al. showed that the size of the pedicle vessels, which was once considered a challenge because of the small size of the vessels and their tendency for vasospasm,[6,11,21] in children is larger than that in adults when controlling for body size.[9] Complication rates following free tissue transfer for lower limb reconstruction in children have been reported as between 28% and 68%.[22-25] To our knowledge, this is the most extensive systematic review on pediatric lower limb reconstructions with free flaps. Moreover, this is the first systematic review focusing on the difference between free perforator/fasciocutaneous flaps versus free muscular/myocutaneous flaps.

Another concern related to pediatric reconstructive surgery is growth and functional recovery at donor and recipient sites, but earlier reports demonstrate that the

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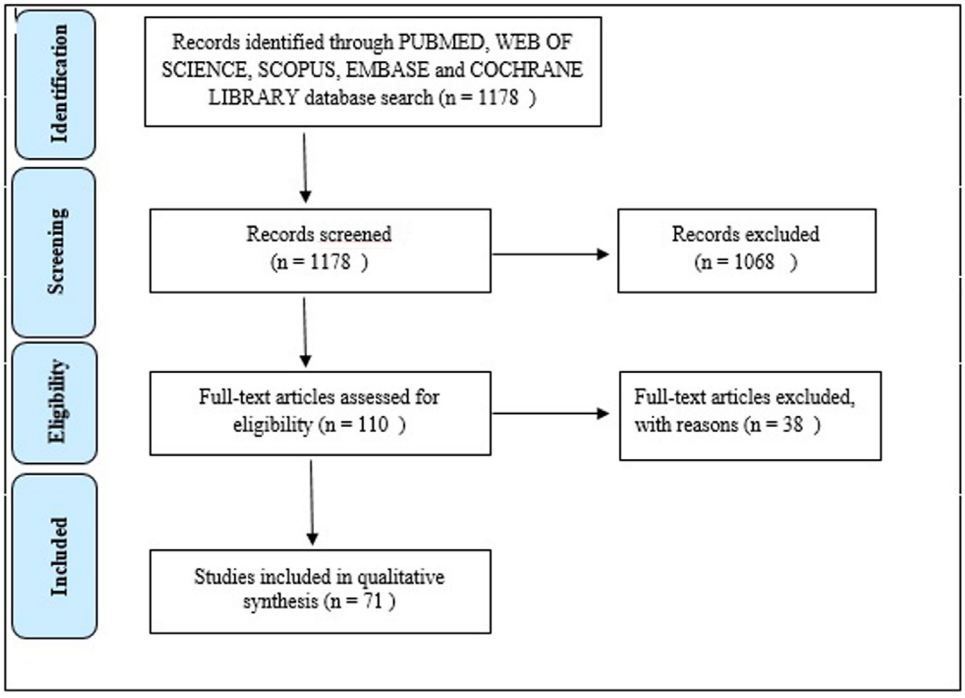

Figure 1 Flowchart according to the PRISMA guidelines.[81,82]

growth pattern in these reconstructed patients is normal.[12-14,26,27]

Objective

The primary objective of this systematic review was to compare the complication rate of free perforator/fasciocutaneous flaps with free muscular/myocutaneous flaps in pediatric lower limb soft tissue reconstructions. The secondary objective was to evaluate the frequency and severity of complications for both reconstructive options.

Methods

Eligibility criteria and information sources

This systematic review was conducted according to the PRISMA protocol (Figure 1).[1] Prior to the literature search, a study protocol was formulated. PubMed, Web of Science, Scopus, Embase, and Cochrane Library database searches were performed depending on inclusion and exclusion criteria defined by the study team. Articles included were reports on children and adolescents between 0 and 18 years old who underwent a lower limb free flap reconstruction for a soft tissue defect with description of the complications and revisions. Exclusion criteria were free flap reconstructions performed for reasons other than lower limb soft tissue defects, replants, and the absence of outcomes data. The studies included were case-reports, meta-analyses, randomized controlled trials, reviews, and systematic reviews. The literature search started with the first reports on microsurgical lower limb reconstructions in children published in the 1970s. The last literature search was performed on August 16, 2018. The extensive publication period of 40 years resulted in a risk for bias. For example, most groin flaps were described in earlier articles, and the complications at that time are difficult to compare with those occurring in more recently described flaps like the superficial circumflex iliac artery perforator (SCIAP) flap. In all articles, no children underwent a reconstruction with two different flaps. If one article reported on more than one flap type in their pediatric population, we described the data of each flap in the appropriate chapter/table.

Database search and study selection

A flow diagram of the search strategy is provided in Figure 1.

The title and abstract of all 1178 studies retrieved through the database search were examined by 4 reviewers (KC, DO, ED, and CS) (Table 1). In cases where suitability for inclusion was unclear, the entire article was obtained and assessed. Eligibility in the review was determined by the inclusion and exclusion criteria as previously described. This resulted in exclusion of 1068 articles.

In the next phase, methodological quality of each full-text article was assessed by 2 reviewers for eligibility using the QUADAS tool.[28] In the case of discrepancy between the two reviewers, the senior authors (KVL and NR) decided on the methodological quality. During the assessment, a manual search of the reference list of the citations was performed. This phase excluded another 38 studies and resulted in the inclusion of 71 articles for the systematic review.

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Table 1 Database and study selection.

PubMed database search (MESH-terms)	((“Lower Extremity”[Mesh]) AND (“Child”[Mesh] OR “Child, Preschool”[Mesh])) AND “Free Tissue Flaps”[Mesh]) AND “Adolescent”[Mesh])
PubMed database search (General terms)	((“Lower extremity” AND “reconstruction” AND “Children” AND “free flap”)); a Web of Science search (TS=(“Lower extremity” AND “reconstruction” AND “Children” AND “free flap”) AND DOCUMENT TYPES: (Article); Timespan: All Years)
Scopus database search	a (Lower AND extremity AND reconstruction AND adolescent AND children AND free AND flap, PUBYEAR > 1970. AND (LIMIT-TO (EXACTKEYWORD, "Human")) AND (LIMIT-TO (LANGUAGE, "English") OR LIMIT-TO (LANGUAGE, "French"))
Embase database search	(('child'/exp OR 'child') AND ('adolescent'/exp OR adolescent) AND lower AND ('limb'/exp OR limb) AND ('reconstruction'/exp OR reconstruction) AND freeAND ('flap'/exp OR flap) AND ([cochrane review]/lim OR [systematic review]/lim OR [meta-analysis]/lim OR [controlled clinical trial]/lim OR [randomized controlled trial]/lim) AND ([article]/lim OR [article in press]/lim OR [review]/lim) AND ([dutch]/lim OR [english]/lim OR [french]/lim) AND ([male]/lim OR [female]/lim) AND ([child]/lim OR [adolescent]/lim) AND [humans]/lim AND [embase]/lim AND [1970-2018]/py and PICO search ('child'/exp AND 'preschool child'/exp AND 'lower limb'/exp AND 'reconstructive surgery'/exp AND 'free tissue graft'/exp AND 'complication'/exp AND 'plastic surgery'/exp)
Cochrane library search	(child AND adolescent AND lower limb AND reconstruction AND free flap in Title Abstract Keyword - in Cochrane Reviews, Cochrane Protocols, Trials (Word variations have been searched)
Total search	**1178 studies**

This paucity of well-designed, homogeneous studies addressing lower limb reconstruction with free flaps in children makes it impossible to make a quantitative analysis by means of a meta-analysis.

Results

Perforator flaps

Free anterolateral thigh (ALT) flap

The free ALT flap was the most commonly used flap in 97 patients aged between 2.5 and 18 years (Table 2). The types of injury included burn contractures, lawn mower accidents, MVA, machine accidents, and bicycle accidents. The complication rate was low (11.3%), although it resulted in 3 partial (3%) and 1 total (1%) flap failures. One in five flaps needed additional surgical procedures such as debulking and one patient needed a STG for partial necrosis.

Thoracodorsal artery perforator (TDAP) flap

Twenty-one patients aged between 6 months and 17 years underwent reconstruction of the knee, lower leg, and foot with a free thoracodorsal artery perforator (TDAP) flap after trauma, sepsis, iatrogenic strangulation, and scar contracture. The complication rate was 38% and 2 patients experienced a total flap loss (9.5%). Revision rate was 24%: closure of wound dehiscence or redo flap reconstruction due to necrosis of the previous flap (Table 3).

Free deep inferior epigastric artery perforator (DIEAP) flap

Seven patients, aged between 4 and 16 years, underwent reconstruction with a free DIEAP flap (Table 4) for degloving injuries and neurofibroma resection. Although the complication rate was very high (71%), owing to the high number of complications in one series,[9] there was only one partial failure. Almost half (43%) of the flaps needed secondary procedures: debulking with liposuction and debridement procedures followed by flap advancement/split-thickness skin graft (STG) for wound closure.

Free superficial inferior epigastric artery perforator (SIEAP) flap

One author described the use of 3 SIEAP flaps in 2 patients for the reconstruction of major soft-tissue defects after meningococcal septicemia (Table 5). One patient had a small wound dehiscence treated conservatively.

Free lateral arm flap

Two reports were found: one describing reconstruction of an unstable scar in a 7-year-old boy (Table 6) and another for an avulsion of the dorsum of the foot with tendon lesion.[47] Both cases were uneventful.

Free profunda artery (PAP) flap

Only one report described a vertically oriented profunda artery perforator (PAP) flap for the coverage of 2 lower limb soft-tissue defects due to an all-terrain vehicle accident (Table 7). No flap complications were encountered, and one child needed minor flap debulking.

Free peroneal artery perforator flap

Ozkan and colleagues described the results of free peroneal artery perforator flaps in 2 children (Table 8). No complications and minimal donor site morbidity were reported.

Fasciocutaneous flaps

Free radial forearm (RFA) flap

Sixteen patients, aged between 3 and 16 years, underwent reconstruction with free radial forearm (RFA) flap (Table 9).

Table 2 Anterolateral thigh (ALT) flap.

Study/Study type	Age (Year)/ Gender (Male or female)	Etiology/Flap (cm × cm or cm^2)	Follow-up (Months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Segev et al.[29]	8 and 12 years 1 male 1 female	Burn contracture dorsum feet and lawn mower accident foot/No information	No information	No complications	None described
Yildirim et al.[30]	7 years No information	Trauma medial malleolus/No information	48	No complications	None described
Demirtas et al.[24]	4-6 years 4 males 1 female	Car tire injury foot/8 × 5 cm-12 × 7 cm	18-41	Hematoma (1 child, 20%) Infection (1 child, 20%)	None described
Gharb et al.[31]	5-18 years 7 males 1 female	Trauma, crush trauma, scleroderma resection, burn contracture, fracture, ulcer leg, ankle foot 4 × 6 cm-25 × 8 cm	No information	Proximal and distal tip necrosis (1 child, 12.5%) Hypertrophic scarring (1 child, 12.5%) Venous thrombosis (1 child, 12.5%)	None described
Acartürk[32]	9 years 1 female	MVA left foot 16 × 8 cm skin, 6 × 18 vastus lateralis and 2 × 14 cm femur	12	No complications	None described
El-Gammal et al.[33]	2.5-13 years 32 males 10 females	Trauma ankle and foot Mean 15.5 ± 2.72 cm x 7.44 ± 1.28 cm	12	Venous congestion with partial (2 children, 5%) and complete (1 child, 3%) failure after reanastomosis	Debulking (15 children, 36%)
Venkatramani et al.[34]	12-16 years; 1 male, 1 female	Trauma thigh and knee 25 × 10 cm-30 × 15 cm	No information	No complications	Bone grafting for femur (1 child, 50%)
Acar et al.[35]	3-15 years 8 males 3 females	MVA, agricultural machinery accident, bicycle chain accident ankle and foot 8 × 6 cm-13 × 9 cm	13-29	Venous thrombosis with partial necrosis after salvage (1 child, 9%)	STG for partial necrosis (1 child, 9%)
Hu et al.[36]	4.5-14 years 16 males 9 females	MVA, machine accident ankle, heel and foot 5 × 8 cm-12 × 18 cm	6-24	2 limited distal necrosis (2 children, 8%)	Debulking (5 children, 2%)
Total	**2.5-18 years 69 males 27 females**	**24-450 cm^2**	**6-48**	**11/97 flaps = 11.3%**	**19/97 flaps = 19.5%**

Indications for reconstruction were tumor resection, MVA, lawn mower accidents, burn scars, or gunshot wounds. The complication rate was low (16% (3 out of 19 flaps)). No total or partial flap failures occurred. Sixteen percent of flaps needed secondary procedures: expansion at the donor site to replace the skin grafts ($n = 2$) and a debulking procedure ($n = 1$).

Groin flap

The groin flap was used in older publications: 14 children between 2 and 18 years old underwent 15 free flap reconstructions after traffic accidents (Table 10). There was a 21% complication rate with partial necrosis in 3 children. Three flaps needed additional debulking procedures.

Free parascapular flap

Six male patients, aged between 4 and 12 years, had reconstruction with a free parascapular flap after MVA, a hunting accident, and a sarcoma resection (Table 11). Fifty percent had complications, but they were minor: flap tip necrosis treated with debridement and delayed primary closure. No partial or total flap failure occurred.

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Table 3 Thoracodorsal artery perforator (TDAP) flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Van Landuyt et al.[9] Case series	6 months-16 years/ 5 males 6 females	Degloving, sepsis, tumor resection, lawnmower accident, defenestration, crush trauma, iatrogenic strangulation lower leg and foot/No information	No information	Wound dehiscence (3 children, 27%); Arterial revision (1 child, 9%); Ongoing necrosis (1 child, 9%); Total failure (1 child, 9%)	Closure wound dehiscence (1 child, 9%); Shortening wound metatarsal heads (2 children, 18%); Treatment ongoing necrosis with cross-leg, gastrocnemius, and fasciocutaneous flap After 5 years of reconstruction with a bipedicled DIEAP flap for esthetic reasons (1 child, 9%); Lower leg amputation due to total failure (1 child, 9%)
Lee and Mun[37] Case series	7-16 years/ 5 males, 5 females	Trauma, scar contracture, knee, ankle foot/7 × 5-16 × 9.5 cm	10-29	Total flap loss due to arterial failure (1 child, 10%); Vein revision (1 child, 10%) Donor dehiscence (1 child, 10%)	None described.
Total	**6 months-16 years 10 males 11 females**	**35-152 cm^2**	**10-29**	**8/21 flaps = 38%**	**5/21 flaps = 24%**

Table 4 Deep inferior epigastric artery perforator (DIEAP) flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (Months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Van Landuyt et al.[9] Case series	4-15 years/ 4 males, 2 females	Degloving injury lower leg, ankle, foot/No information	No information	Arterial revision (1 child, 17%); Partial failure (1 child, 17%); Wound dehiscence (2 children, 33%); Wound edge necrosis (1 child, 17%)	Debridement + advancement flap due to partial failure (1 child, 17%); Liposuction (1 child, 17%); Debridement and STG due to wound edge necrosis (1 child, 17%)
Grinsell et al.[44] Case series	16 years/ 1 female	Neurofibroma lower limb/26 × 19 cm	0.5	No complications	None described
Total	**4-16 years 4 males 3 females**	**494 cm^2**		**5/7 flaps = 71%**	**3/7 flaps = 43%**

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Table 5 Superficial inferior epigastric artery (SIEAP) perforator flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (Months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Van Landuyt et al.[9] Case series	9 and 12 years/ 2 males	Meningococcal septicemia lower leg, ankle, foot/No information	No information	Wound dehiscence (1 child, 33%)	None described

Table 6 Lateral arm flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Shapiro et al.[15] Case series	7 years/ 1 male	Unstable scar foot/3 × 3 cm	19	No complications	None described
Merlino et al.[47]	8 years/ 1 male	Avulsion dorsum foot/7 × 10 cm	No information	No complications	None described
Total	**7-8 years 2 males**	**9-70 cm^2**	**19**	**0/2 flaps = 0%**	**0/2 flaps = 0%**

Table 7 Profundal Artery Perforator (PAP) flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Mayo et al.[48] Case series	4 and 12 years 1 male No information about other child	All-terrain vehicle and Go Kart accidents. Both 13 × 5 cm	0.75	No complications	Minor flap debulking (1 child, 50%) No information about other child

Table 8 Peroneal artery perforator flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Ozkan et al.[49] Case series	6 and 8 years/ 2 males	Trauma distal leg, foot Both 4 × 2 cm	9-12	No complications	None described

Free scapular flap

Four male and 1 female patient, aged between 4 and 16 years, underwent free scapular flap reconstruction for soft tissue defects after lawn mower accidents, a gunshot wound, or a posterior medial release (Table 12). The complication rate was high (40%), although the 2 complications involved were minor. No flap failure was described, and only 1 patient underwent a secondary debulking procedure.

Muscle/myocutaneous flaps

Latissimus dorsi (LD) muscle/myocutaneous flap

Ninety children, aged between 15 weeks and 17 years, underwent reconstruction with 93 free latissimus dorsi (LD) muscle or myocutaneous flaps for various reasons (MVA, lawn mower accident, burn trauma, tumor resection, and septic shock) (Table 13). This was the second largest group

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Table 9 Free Radial Forearm (RFA) flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Serletti et al.[14] Case series	4-16 years/ 4 males, 2 females	Tumor, Mower, motor vehicle accident, infection ankle, foot / No information	8-31	Venous thrombosis (1 child, 17%)	Tissue expander for subsequent removal of the skin-grafted donor site (2 children, 33%)
Kaplan et al.[38] Case series	14 years/1 male	Traffic accident foot 11×22 cm	3	No complications	None described
Weinzweig et al.[39] Case series	3-16 years/3 males	Trauma, gunshot wound leg and ankle/40-120 cm^2	14-72	No complications	None described
Yucel et al.[40] Case series	5-8 years 1 male, 2 females	Burn, vehicle accident sole, midplantar, heel/No information	1-38	Superficial ulcer (2 children, 67%)	Excision excessive flap tissue and flap insetting (1 child, 33%)
Kuran et al.[41] Case series	16 and 18 years/ 2 males	Avulsion, unstable burn wound heel 6×7 cm-8×7 cm	3-6	No complications	None described
Yucel et al.[16] Case series	5-8 years/ 2 males, 2 females	Burn scar, trauma lower leg, heel, plantar, No information	4-40 No information	Flap revision (1 child, 25%)	None described
Total	**3-16years/ 13 males 6 females**	**40-242 cm^2**	**1-72**	**3/19 flaps = 16%**	**3/19 flaps = 16%**

of children. The reconstructions resulted in a 32% complication rate. A total loss of 3 flaps (3%) and a partial loss of 4 flaps (4%) were reported. One-third of the flaps needed secondary procedures such as debulking and regrafting of the muscle.

Free rectus abdominis muscle/myocutaneous flap

The free rectus abdominis (RA) muscle/musculocutaneous flap was used for the reconstruction of soft tissue defects on the ankle, heel, or foot in 5 children aged between 14 and 18 years. The etiologies were MVA, tumor resection, burn, and gunshot wounds (Table 14). The only complication reported was osteomyelitis; no flap failures or secondary procedures were described.

Free gracilis flap

The gracilis flap was also a quite frequently used flap in the pediatric population aged between 2 and 18 years (Table 15). Twenty-four soft tissue defects on the lower leg and foot due to MVA, lawn mower accidents, gunshots, and trauma were reconstructed. The complication rate was 21%, with only one (4%) partial flap loss. No secondary procedures were described.

Discussion

The critical factor in determining the suitability of free tissue transfer is the perceived salvage ability of the lower limb.[61] To aid clinicians in this decision making regarding limb salvage or early amputation, a number of limb salvage scoring systems have been developed, e.g., mangled extremity severity score (MESS),[62] predictive salvage index (PSI),[63] and NISSA score.[64] The second highly discussed topic in lower extremity reconstruction is flap choice. Overall, the (pediatric) reconstructive surgeon has to choose between a muscle and a skin flap:

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Table 10 Groin flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (Months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Harii et al.[17] Case reports	4 and 4.5 years/ 2 males	Traffic accident lower leg, ankle 9×7 and 12×6 cm	1-1.5	No complications	None described
Baudet et al.[65] Case series	14 and 18 years/ 1 male, 1 female	Traffic accident lower leg, foot/12×8 cm-19×10 cm	0.5	No complications	None described
Iwaya et al.[42] Case series	2-8 years/ 4 males, 1 female	Avulsion injury dorsum foot/13×5.5 cm-10×19 cm	3, No information in other 4 cases	Thrombosis (1 child, 20%); Partial necrosis (2 children, 40%)	None described
Chiang et al.[13] Case series	3-6 years/ 3 males, 2 females	Soft tissue defect ankle, foot/No information	16-95	No complications	Debulking (3 children, 60%)
Total	2-18 years 10 males 4 females	63-190 cm^2	0.5-95	3/14 flaps = 21%	3/14 flaps = 21%

Table 11 Parascapular flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (Months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Moghari et al.[26] Case series	4-6 years/ 4 males	Motor vehicle accident with deglovement knee and leg/No information	1-12	Tip necrosis (3 children, 75%)	Debridement tip necrosis and primary closure (3 children, 75%)
Hallock[45] Case series	12 years/ 1 male	Hunting accident, posterior thigh/8×25 cm	No information	No complications	None described
Saito et al.[46] Case series	12 years/ 1 male	Soft tissue sarcoma resection ankle/No information	28	No complication	Amputation due to recurrence
Total	**4-12 years 6 males**	**8 x 25 cm**	**1-28**	**3/6 flaps = 50%**	**3/6 flaps = 50%**

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Table 12 Scapular flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Parry et al.[6] Case series	14 years/ 1 female	Soft tissue defect heel/No information	18	No complications	None described
Shapiro et al.[15] Case series	4 years/ 1 male	Failed posterior medial release foot/10 × 20 cm	27	Dehiscence (1 child, 100%)	None described
Serletti et al.[14] Case series	16 years/ 1 male	Gunshot wound foot/No information	45	No complications (1 child, 100%)	2 debulking procedures
Erdmann et al.[23] Case series	5 years/ 1 male	Lawn mower accident heel/No information	3	Hematoma flap (1 child, 100%)	None described
Saito et al.[46]	12 years/ 1 male	No information	28	No complication	Amputation due to recurrence 2 y after surgery
Total	**4-16 years 4 males 1 female**	**130-200 cm^2**	**3-45**	**2/5 flaps = 40%**	**1/5 flaps = 20%**

Muscle flap:
− Leads to functional loss at the donor site
− Needs a split-thickness skin graft (STG) for coverage, which leads to a higher donor site morbidity and additional scarring.
− Difficult to shape and reshape. Makes subsequent procedures (e.g., orthopedic) more difficult.
+ Fills dead space
+ Provides additional vascularity to the wound
+ Allows flexibility of positioning and pedicle placement

Skin flap:
+ Can be sensate with inclusion of a sensory nerve.
+ Pliable and thin
+ Can be reshaped in secondary (e.g., orthopedic) procedures when there is a need to make an incision over the previous scars.
− Pedicle dissection more time-consuming
− Additional muscle needed to create flap bulkiness

In contrast to the findings in the systematic review of Jabir et al.,[25] the most common reconstructive choice in our review was the perforator flap (134 flaps), followed by the muscle flap (122 flaps) and the fasciocutaneous flap (44 flaps). The muscle flap was employed more in the initial studies.

The ultimate goal of reconstructive surgery is to replace like with like to optimally restore not only function but also form and contour of the lower limb. The reconstruction of tissue defects has to be planned carefully with regard to the specific pediatric anatomy and the evolution of children's tissue and skeletal structures. Apart from these surgical considerations, psychosocial ramifications and discomfort of prolonged disability at a young age have to be kept in mind.

The summary of all flaps in this systematic review is given in Table 16. The second most commonly used flap was the LD muscle flap, which is a reflection of the overall literature on extremity soft tissue reconstruction. It is considered the most reliable of all free-tissue transfers for the lower extremity.[66,67] In this systematic review, with a low complication rate of 11.3% and partial and total flap loss of 3% and 1%, respectively, the ALT flap can be considered more reliable. Development of shoulder and chest is very important, which may be hampered after complete removal of the LD muscle.[25] Partial muscle harvest with preservation of residual muscle function is beneficial in children.[68,69] This in contrast to the perforator flaps, which preserves the muscles. However, in comparison with perforator flaps, the LD flap offers a large amount of tissue, as it is the largest flap, that can be transferred to surface areas up to 750 cm^2. A constant vascular anatomy enables straightforward dissection and long (average 9 cm) and high-caliber vessels (2.5-4.0 mm) combined with a low donor site morbidity.

Skin flaps, like the fasciocutaneous flaps, are preferred when there is no necessity to include bulk or provide a functional reconstruction. In contrast, perforator flaps make up the majority of free flap procedures worldwide. These flaps provide larger skin islands with longer pedicles and less donor site morbidity based on well-known and sizable source vessels. An excellent example is the TDAP flap: in cases with critical skin shortage (e.g., in meningococcal sepsis), it has the advantage of being the second largest skin flap amenable to primary closure. TDAP flaps leave scars with less contour deformity on a relatively hidden area. An additional advantage is its possible use as a compound flap. The flap can be re-innervated through the intercostal branches to provide sensation if necessary.[37] In this review, the complication rate was slightly higher than that in the LD

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Table 13 Latissimus dorsi muscle/myocutaneous (LD) flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up period (months)	Complications (No. of children,% of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Iwaya et al.[42] Case series	6-14 years/ 2 males	Avulsion injury dorsum foot/15 × 24 cm and 20 × 10cm	3-12	Superficial necrosis (1 child, 50%)	STG (1 child, 50%)
Banic and Wulff[11] Case series	3-9 years/ 10 males, 5 females	Automobile accident injury lower leg, ankle, dorsum foot/15 × 8 to 24 × 11	1-24	Arterial revision (1 child, 7%); Arterial revision with partial loss (1 child, 7%)	STG zone of necrosis (1 child, 7%); Regraft back (4 children, 27%)
Parry et al.[6] Case series	6-13 years/ 3 males	Soft tissue defect ankle, anterior tibial/No information	12-48	No complications	None described
Shapiro et al.[15] Case series	6-16 years/ 3 males, 5 females	Trauma, osteomyelitis knee, leg, foot 5 × 8 cm to 25 × 30 cm	8-25	Wound infection (2 children, 25%); Partial failure STG (1 child, 12.5%)	Reapplication STG (1 child, 25%)
Serletti et al.[14] Case series	3-17 years/ 4 males, 3 females	Crush trauma, motor vehicle accident, mower, burn ankle, heel, foot/No information	11-59	No complications	Posterior ankle release (1 child, 14%)
Chiang et al.[13] Case series	2-13 years/ 10 males, 5 females	Motor vehicle accident, release scar contracture ankle, heel, foot/No information	8-95	Venous obstruction (3 children, 18%); Partial loss (2 children, 12%); Loss STG due to infection (1 child, 6%); Hematoma donor site (1 child, 6%)	New free flap (1 child, 6%)
Kaplan et al.[38] Case series	8 and 10 years 2 males	Traffic accident knee and foot/10 × 16 cm-12 × 24 cm	1.5-20.5	No complications	None described
Erdmann et al.[23] Case series	2-4 years/ 4 males	Lawnmower trauma knee, heel, foot/No information	3	Venous revision (1 child, 25%); Seroma donor site (1 child, 25%)	Multiple procedures performed without specific information.
Kuran et al.[41] Case series	6 years/ 1 male	Crush avulsion left foot/15 × 10 cm	24-168	No complications	Contour revision and volume reduction (1 child, 100%)
Yucel et al.[16] Case series	15 years/ 1 male	Electrical burn injury right ankle/No information	40	No complications	None described
Gonzalez et al.[50] Case series	7 years/ 1 male	Motor vehicle accident ankle/7 × 22 cm	17	No complications	None described

(*continued on next page*)

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Table 13 (*continued*)

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up period (months)	Complications (No. of children,% of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Lickstein and Benz[4] Case series	4 and 7 years/ No information about 2 patients	Motor vehicle accident lower leg/No information	No information	Dusky appearance (1 child, 50%); Anastomotic revision (1 child, 50%)	Delay STG due to dusky appearance (1 child, 50%)
Ozkän et al.[51] Case report	8 years/ 1 female	Motor vehicle accident/7 × 18 cm	10	No complications	Exploration distal part flap and debridement nonviable remnants of metatarsal bones (1 child, 100%)
Germann et al.[52] Case report	15 weeks/ 1 male	Tumor resection/6.5 cm x 5 cm	12	No complications	Debulking flap (1 child, 100%)
Yildirim et al.[30] Case series	6-15 years/ No information about 3 patients	Trauma leg and dorsum foot/No information	20-32	No complications	Release contracture toe with eventual amputation in 1 patient (33%), no information about the other 2 patients
Hallock[45] Case series	12 years/ 1 male	Hunting accident lower leg/8 × 25 cm	No information	No complications	None described
Bouffaut et al.[53] Case series	3-14 years/ No information about 4 patients	Mowing accident, purpura/72-300 cm^2	24-48	No complications	None described
Namdar et al.[54] Case series	4-17 years/ 8 males, 3 females	Lawn mower accident, traffic accident, crush trauma/No information	No information	4 major revisions: reanastomosis and 9 minor revisions with complete loss of 3 and partial loss in 1 flap (10 patients, 93%)	None described
Wechselberger et al.[55] Case report	15 months/ 1 male	Septic shock with soft tissue necrosis lower legs/5 × 4 cm	19	Wound dehiscence (1 child, 100%)	Skin mobilization (1 child, 100%)
Venkatramani et al.[34] Case series	6-15 years/ 2 males, 1 female	Trauma knee/7 × 5 cm - 25 × 12 cm	No information	Arterial thrombosis (1 child, 33%)	Cross leg flap as replacement reconstruction (1 child, 33%)
Rednam et al.[56] Case report	8 years/ 1 male	Crush injury lower leg/100 cm^2	24	No complications	Debridement of residual defect and STG coverage (1 child, 100%)
Song et al[57] Case series	6-11 years/ 3 males	Avulsion injuries 12 × 7 cm - 18 × 12 cm	5.3-9.2	Partial loss skingraft (1 child, 33%)	Secondary skin grafting (1 child, 33%)
Total	**15 weeks-17 years** **58 males** **23 females**	**20-750 cm^2**	**1.5-168**	**30/93 flaps = 32%**	**27/93 flaps = 29%**

Table 14 Rectus abdominis muscle/myocutaneous flap.

Study/Study type	Age (Year)/Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Serletti et al.[14] Case series	14-17 years/ 3 males	Motor vehicle accident, tumor, burn heel, ankle and foot/No information	11-58	No complications	None described
Gonzalez et al.[50] Case series	18 years/ 1 male	Gunshot wound foot/7 × 12 cm	49	Local osteomyelitis (1 child, 100%)	None described
Bouffaut et al.[53] Case series	15 years/ No information	Traffic accident foot/50 cm^2	12	No complications	None described
Total	**14-18 years 4 males**	**50-84 cm^2**	**11-58**	**1/5 flaps = 20%**	**0/5 flaps = 0%**

Table 15 Gracilis flap.

Study/Study type	Age (Year) Gender (Male or female)	Etiology/Flap (cm x cm or cm^2)	Follow-up (Months)	Complications (No. of children, % of total amount of flaps)	Secondary procedures (No. of children, % of total amount of flaps)
Parry et al.[6] Case series	2-11 years/ 4 males, 5 females	Gunshot wound, trauma lower leg, ankle, heel/No information	18-48	No complications	None described
Chiang et al.[13] Case series	6-14 years/ 3 males	Trauma lower leg, ankle, heel/No information	54-89	No complications	None described
Yucel et al.[16] Case series	17 years/ 1 male	Trauma left heel/No information	8	Wound infection (1 child, 100%)	None described
Lorea et al.[58] Case series	9 and 11 years/ 1 male, 1 female	Composite wound and tibial fracture/20 and 32 cm^2	6-7	No complications	None described
Lickstein and Benz[4] Case series	3-18 years/ No information	Lawnmower accident, motor vehicle accident foot/No information	No information	Anastomotic revision with partial loss of flap (1 child, 14%); Fever hematoma (1 child, 14%); Hypertrophic scarring (1 child, 14%); Ureteral obstruction (1 child, 14%)	**None described**
Franco et al.[60] Case series	5-13 years/ 3 males, 1 female	Motor accident in lower leg/No information	No information	No complications	**No secondary procedures**
Total	**2-18 years 12 males 7 females**	**10-32 cm^2**	**6-89**	**5/24 flaps = 21%**	**0/24 flaps = 0%**

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Table 16 Summary.

Reconstructive method	Age (Year) Gender (Male or female)	Flap (cm x cm or cm^2)	Follow-up (Months)	Complications (% of total amount of flaps)	Secondary procedures (% of total amount of flaps)
ALT	2.5-18 years/ 69 males, 27 females	24-450 cm^2	6-48	11/97 flaps = 11,3%	19/97 flaps = 19.5%
TDAP	6 months-16 years/ 10 males, 11 females	35-152 cm^2	10-29	8/21 flaps = 38%	5/21 flaps = 24%
RFA	3-16 years/ 13 males, 6 females	40-242 cm^2	1-72	3/19 flaps = 16%	3/19 flaps = 16%
Groin	2-18 years/ 10 males, 4 females	63-190 cm^2	0.5-95	3/14 flaps = 21%	3/14 flaps = 21%
DIEAP	4-16 years/ 4 males, 3 females	494 cm^2	0.5	5/7 flaps = 71%	3/7 flaps = 43%
Parascapular	4-12 years/ 6 males	8 × 25 cm	1-28	3/6 flaps = 50%	3/6 flaps = 50%
Scapular	4-16 years/ 4 males, 1 female	130-200 cm^2	3-45	2/5 flaps = 40%	1/5 flaps = 20%
SIEAP	9 and 12 years/ 2 males	No information	No information	1/3 flaps = 33%	0/3 flaps = 0%
Lateral arm flap	7-8 years/ 2 males	9-70 cm^2	19	0/2 flaps = 0%	0/2 flaps = 0%
PAP	4 and 12 years/ 1 male	13 × 5 cm	0.75	0/2 flaps = 0%	1/2 flaps = 50%
Peroneal Artery Perforator	6 and 8 years/ 2 males	4 × 2 cm	9-12	0/2 flaps = 0%	0/2 flaps = 0%
LD	15 weeks-17 years/ 58 males, 23 females	20-750 cm^2	1.5-168	30/93 flaps = 32%	27/93 flaps = 29%
RA	14-18 years/ 4 males	50-84 cm^2	11-58	1/5 flaps = 20%	0/5 flaps = 0%
Gracilis	2-18 years/ 12 males, 7 female	10-32 cm^2	6-89	5/24 flaps = 21%	0/24 flaps = 0%

group (38%), but the total flap loss was twice as high (9.5%), which makes it a less reliable reconstructive option.

The ALT flap was the most frequently reported flap (97 patients with 97 flap reconstructions). It has the advantage of transferring large skin paddles and different tissue types on a large and long pedicle, the potential for thinning, reinnervation, flow-through revascularization, and coverage of extremities with minimal donor site morbidity.[70] As already mentioned, this was accompanied with a low complication rate and amount of secondary procedures (11.3% and 19.5%, respectively).

Other reconstructive methods can be considered as a second choice on the basis of their low incidence, and their indication for use depends on the case and the experience of the surgeon. With its low rate of complications and secondary procedures (16% for both), the RFA fasciocutaneous flap seems an excellent option for lower limb reconstruction because it can be combined with bone,[71-73] tendons,[73] or cutaneous nerves.[72-74] The huge disadvantages remain the cosmetically unacceptable appearance of the donor site and the sacrifice of the main artery to the hand, which could lead to functional impairment. Like the RFA flap, the lateral arm flap can also be used in a variety of reconstructive procedures because it is a thin, soft, and sensory tissue flap that offers a suitable amount of color-matched tissue and low donor site morbidity. The drawback is that it is only advantageous for smaller defects to avoid skin grafting at the donor site. Both the scapular and parascapular fasciocutaneous flaps are also thin flaps with low donor site morbidity. In this review, there was a high rate (40% and 50%) of minor complications. such as tip of the flap necrosis, dehiscence, and a hematoma. Scapular and parascapular flaps are good options in case of the need for a chimeric flap (osteocutaneous scapular flap or combination with the parascapular

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flap). The drawback of both flaps, as well as for the LD or TDAP flap, is that the patient has to be turned after flap harvest.

Patient repositioning is not necessary when using the RA flap, which is a frequently used flap according to the literature although this could not be confirmed in this systematic review. On the basis of low complication rates, it seems a primary reconstructive option for lower limbs. A major drawback of harvesting an RA flap is abdominal wall weakness or even herniation of intra-abdominal contents. The DIEAP flap can overcome these issues providing a large skin flap, if necessary, based on 2 separate pedicles. Unfortunately, primary closure of the donor site is not always possible in children. In this review, there was a very high complication rate (71%), but most complications described were minor.

The gracilis flap is another less commonly used flap owing to its smaller vascular pedicle and smaller size. The flap width can be extended considerably, on average, by more than 100% by removal of the epimysium. This allows coverage of defects measuring up to 300 cm^2[75] with minimal donor site morbidity.[58,59]

Other flaps such as the SIEAP, PAP, and peroneal artery perforator flap were less frequently described and not detailed enough to give appropriate comment about its use in lower limb reconstruction in children.

Regarding donor vessels, it can be difficult to expose major vessels and, frequently, a major vessel has to be sacrificed to anastomose the flap. However, using small branches from the major vessel or using a perforator as a recipient vessel may prevent this issue.[76] The supermicrosurgery approach for lower extremity reconstruction in a perforator-to-perforator anastomosis can result in the same success without sacrificing major vessels and may further reduce operative time by minimally dissecting the flap vessels and recipient site vessels.[19]

Another potential problem related to pediatric reconstructive surgery is the growth and functional recovery at the donor and recipient sites. In most pediatric patients, the musculoskeletal system continues to grow after surgery and the possibility of contractures always remains. However, earlier reports observed that the growth pattern in these patients is within the normal range.[12,14,26,27] Canales et al.[12] identified no growth-related complications for both donor and recipient sites in their large series of microvascular tissue transfers. This could be confirmed by Serletti et al.[14] during their mean follow-up period of 31 months. Others described problems such as a limping gait, flap ulcers, toe contractures, or bulky flaps during an average follow-up of approximately 5 years.[13] The latter should not be ignored on a foot. Staged debulking procedures alleviate the problems of footwear and psychological impact. Because children are usually physically active, prone to ignore the care of their reconstructed heels, the risk of flap ulcers in weight-bearing heels remains high. A well-tailored flap and good postoperative care including orthoses and other devices are as important as sensation and durability in reconstructing weight-bearing heels in children.[66,77,78] Both Chiang et al.[13] and Iwaya et al.[42,43] reported a case with slightly impeded growth of the reconstructed foot. Chiang et al. found no evident difference in growth rate between skin flaps, muscle flaps with split-thickness skin graft, and myocutaneous flaps.[13] In addition to debulking procedures to improve the esthetic aspect and alleviate footwear issues, there were no growth and functionality-related problems described that needed a secondary procedure.

Because of a decrease in donor site morbidity as a result of the preservation of muscle innervation, vascularization, and functionality of the donor muscle; less postoperative pain; and a swifter rehabilitation, the perforator flap is considered the best option for reconstructive purposes. The advantages of harvesting relatively large and thin skin flaps include the absence of postoperative muscle atrophy as seen in myocutaneous flaps, the presence of long vascular pedicles based on well-known source vessels, and the possibility of harvesting sensory nerves with the flap, providing a tool to perform more accurate and precise reconstructions. Given that an ideal reconstruction should replace "like with like," and the knowledge that approximately 80% of free flaps are used for resurfacing purposes and only a minority of patients need a free flap to fill up dead space or deep defects, free flaps consisting of skin and subcutaneous fat tissue are predominantly needed in daily practice.[79]

Therefore, the free ALT is considered the best option for lower limb reconstruction in children. No articles reporting on the SCIAP flap for lower limb reconstruction in children were included from the database search and study selection, although it can be a safe method of reconstruction, providing ample, extremely pliable tissue that serves as an ideal skin substitute in a variety of anatomic locations, with the advantage of very little donor site morbidity. It is considered the workhorse flap for moderate-sized defects,[80] but like the groin flap, it has the SCIAP, a variable and small vasculature, and relatively short pedicle, which makes it difficult to stay out of the zone of injury in cases of traumatic lower limb defects. The supermicrosurgery approach, described by Hong,[19] has resulted in survival of the SCIAP flap that does not show difference from that seen with conventional microsurgery.

Conclusion

In this review, microsurgical reconstruction of lower extremity defects in the pediatric population has proven to be safe with flap survival rates of more than 90%.

On the basis on the results of this systematic review, the perforator flap must be considered the best reconstructive method for lower limb soft tissue defects in children. The first choice should be the ALT flap with low complications and low incidence of revision. The second choice perforator flap is the TDAP flap, which can provide a large flap with primary closure of the donor site and possible neurotization.

Considering the low complication rate and amount and extent of secondary surgeries, the RFA fasciocutaneous flap can be considered a good alternative for ALT and TDAP flaps. The esthetic aspect of the donor site and the sacrifice of a main artery are drawbacks.

The need for a very large flap should be the only indication to use the LD muscle flap, the second most described free flap in this systematic review. The complication rate is comparable to that of the TDAP flap, but the total flap loss is lower. The functional loss after muscle harvest and the need for a STG is a major drawback.

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Other free fasciocutaneous and perforator flap options are second choice, and their indication for use depends on the case and the experience of the surgeon.

The paucity of well-designed, homogeneous studies addressing lower limb reconstruction with free flaps in children makes it very challenging to draw more extensive conclusions. Unfortunately, it was also impossible to make a quantitative analysis by means of a meta-analysis. More adequate studies specifically concerning free flap reconstructions for lower limb defects in children are necessary in the future to provide guidelines for treatment and optimize outcomes in the long term.

All 6 authors meet all four criteria of authorship according to the recommendations of the International Committee of Medical Journal Editors (ICMJE):

1) Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; AND
2) Drafting the work or revising it critically for important intellectual content; AND
3) Final approval of the version to be published; AND
4) Agreement to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated

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