Clinics in Surgery

Research Article
Published: 19 Nov, 2021

The Reconstructive Ladder for Revision Surgery of Combat Amputees

Ernst Jennifer[1,2], Luis Pardo Jr[1], Judith C Witzel[1], Erik Andres[3], Johannes Siegel[3], Daniela Wüstefeld[3], Wolfgang Lehmann[1], Frank Braatz[1] and Gunther Felmerer[1]*

[1]Department for Trauma Surgery, Orthopedic Surgery and Plastic Surgery, University Medical Center Göttingen, Germany

[2]Department for Trauma Surgery, Hannover Medical School, Hanover, Germany

[3]Ottobock, Patient Care Center Duderstadt, Germany

Abstract

Findings and Outcomes: Combat injury related amputations are associated with a higher number of complications. Little attention has been given to the role of surgical treatment concepts to treat residual limb pain after combat-related amputations and complications at the residual limb. This case series shows the impact of surgery and of the reconstructive ladder in the management of complications after combat injury related amputations for 10 amputees. After conservative treatment methods have been exhausted, a treatment algorithm considering the reconstructive ladder seems to direct the appropriate surgical techniques to targets at the residual limb thereby reducing pain and managing complications at the residual limb. The result is better prosthetic fitting and successful rehabilitation for the amputee.

Conclusion: Revision surgery including microsurgical techniques targeting identified pathology at the residual limb should be considered to reduce residual limb pain and to manage complications after combat-related amputations.

Keywords: Revision surgery; Amputation; Residual limb pain; Phantom limb pain; Neuroma; Scars

OPEN ACCESS

Correspondence:
Jennifer Ernst, Department for Trauma Surgery, Orthopedic Surgery and Plastic Surgery, University Medicine Göttingen, Robert-Koch Straße 40, Germany,
E-mail: Jennifer.Ernst@med.uni-goettingen.de

Received Date: *11 Oct 2021*
Accepted Date*: 08 Nov 2021*
Published Date*: 19 Nov 2021*

Citation:
Jennifer E, Pardo Jr L, Witzel JC, Andres E, Siegel J, Wüstefeld D, et al. The Reconstructive Ladder for Revision Surgery of Combat Amputees. Clin Surg. 2021; 6: 3363.

Background

Combat injury related amputations

Traumatic or combat injury related amputations are associated with a higher number of complications including infection, osteomyelitis, bone abnormalities, (cicatricial) scarring, and painful neuroma formation. Reasons might be the environment on the battlefield and its first-care conditions, and the high-energy mechanism of amputation. Displaced bone fragments, heterotopic ossification (HO), foreign bodies and scar tissue can furthermore cause secondary complications. These factors lead to secondary wound healing, prolonged hospitalization, chronification of pain, compromised socket suspension and thus delayed rehabilitation. Furthermore, explosions or blast injuries can be an independent risk factor for subsequent complications such as Phantom Limb Pain (PLP) and, Residual Limb Pain (RLP) [1,2].

Pain after amputation

Up to 95% of amputees suffer from chronic pain after amputation. Causes of chronic pain after amputation include PLP, RLP, contralateral limb pain, and back pain [2,4]. As the etiology of these different pain qualities determines the appropriate therapy, a precise examination and comprehensive diagnostics are required.

Phantom limb pain (PLP)

Phantom Limb Pain (PLP) describes a pain in a limb that is no longer present. PLP occurs with prevalence up to 85% [4,5]. The exact mechanism for the development of PLP is still unknown. A suggested mechanism is an initiation by changes arising in the peripheries that alter the afferent input that the brain and spinal cord receive, leading to central reorganization [5-9]. A wide range of treatments for PLP have been investigated in the literature. In practice, a multidisciplinary, multimodal approach is often necessary to improve pain and quality of life in patients with PLP. Pharmacological, physical and psychological treatments address those PLP-related pain qualities and may help relieve the pain [6,10]. Most surgical procedures used for phantom pain have been abandonned because of poor results in pain reduction [5,6]. Recently published was the first randomized controlled trial showing how PLP is impacted by Targeted Muscle Reinnervation (TMR) [11].

Residual limb pain (RLP)

In contrast to PLP, RLP is an acute nociceptive pain that can resolve after the wound has healed. Infection or wound dehiscence are known to prolong postoperative pain. RLP can also persist for much longer in certain circumstances and seriously affect long-term rehabilitation and the patient's quality of life. The incidence of chronic RLP ranges from 13% to 71% [5,12-14]. Chronic residual limb pain is defined as pain that outlasts normal wound healing time and can result of a localized pathology or painful neuroma. Localized pathologies can be chronic infection, osteomyelitis, painful neuroma, displaced bone fragments, Heterotopic Ossification (HO), scar tissue, foreign bodies, insufficient or excessive soft tissue coverage at the weight-bearing zone, displacements of muscle slings and neuroma [15].

Patients with RLP are often unable to rehabilitate because the pain limits the load of the residual limb (RL) and the acceptance of the prosthesis. Before surgical revision is considered non-invasive treatments such as desensitization, adaption of the prosthetic socket, etc. should be exhausted to relieve the pain at the residual limb [5,16].

Among RLP, neuromas are one of the major reason (10% to 25%) for revision surgeries. Neuromas may often be overlooked, although their reported rate as cause of chronic pain. Neuromas are benign tumors and occur in every amputation. Abnormal growths of nerve tissue that occur at the end of injured nerve fibers can be very painful [12,16].

So called painful neuroma discharge ectopically and spontaneously from afferent nerves linked to an upregulation of voltage-gated sodium channels in the affected nerves at the amputation site [5,17]. Furthermore, neuroma may have an increased sensitivity to mechanical stimuli [5].

Persistent RLP can be very difficult to treat as up to 55% of those with RLP also suffer from PLP. Identification and differentiation of the dominant factor responsible for the pain can be difficult. Furthermore, both pain qualities can maintain the other. RLP is a risk factor for the development of PLP and insufficient prosthetic fitting, and comorbidities compromising wound healing are significant predictors for RLP [5].

Due to poor results of surgical approaches in the treatment of PLP, so far modern surgical concepts have not been considered widely for the treatment of RLP [5,16]. Common opinion is to avoid surgical revision and to treat RLP similarly to PLP. The shown effects of TMR on PLP and RLP seem to change the paradigms in the treatment of postamputation pain [11].

Current treatment options of painful neuroma

Little attention has been given to the role of peripheral nerve surgery as a treatment option, although microsurgical techniques have been described for a long time to relieve nerve-associated pain [16,18]: there were significant changes on pain, spasms, quality-of-life, and ambulation status following removal of the motor and sensory neuroma with implantation of the proximal nerve ending into adjacent muscle fixed by an epineural suture [16].

Targeted Muscle Reinnervation (TMR) is a new technique redirecting the nerve stumps at the residual limb to biomechanical no longer relevant muscles at the amputation site to permit intuitive control of the myoelectric controlled prostheses [19,20]. The donor nerves are coapted to the motor nerves of the target muscles through small recipient motor nerve branches. Clinical experience also suggests that TMR may serve as an effective therapy for neuroma pain [11]. Within the first randomized controlled trial TMR improved PLP and trended toward improved RLP compared with conventional neurectomy and burying the nerve into a muscle. The trend and the lack to reach statistical significance might be due to the fact that RLP is not solely caused by neuromas, rather often then a combination of painful bone spurs, impaired vascular supply, insufficient soft tissue coverage and other conditions that were not addressed by the analyzed surgical procedure within the trial.

Within this cohort study we analyzed the efficacy of revision surgery to treat residual limb pain and complications in combat amputees following a set-up diagnostic and treatment algorithm following the principles of the reconstructive ladder. Herein, if neuroma was present it was treated by a selective nerve transfer and combined to further standard reconstructive techniques to improve the conditions at the residual limb.

Methods

Inclusion

Within a clinical set-up we established an interprofessional "Interdisciplinary Amputee Outpatient Clinic". On average 100 amputees with amputation-related pain qualities, poor socket suspension and difficult skin conditions, are seen yearly. Within this interprofessional set-up the patients were examined and treated following a defined algorithm (Figure 1).

Data assessment

Preoperatively, the following variables were documented: Self-reported pain (Numeric Rating Scale, (NRS)), quality of pain (burning, numbness, electric), localization of the Hoffmann Tinel (HT) sign was marked and photographed. Postoperatively, the self-reported pain scale pain scale (NRS) and photo documentation was re-assessed after prosthetic fitting was finalized, and the type of fitted prosthetic components were documented. NRS Scores pre- and post-intervention were compared for statistical significance using paired t-test, $p<0.05$ as statistically significant.

Surgical techniques

(Plastic)-surgical techniques and specific amputation revision surgery techniques were used to improve soft tissue coverage of the residual limb following the principles of the the reconstructive ladder [21-25].

Painful neuroma at the residual limb were excised and submitted for pathologic examination, under loupe magnification, the proximal nerve stump was cut back to healthy fascicles, mobilized and transposed out of the weight bearing zone and either (1) buried tension-free into a neighbored muscle after opening the fascia and sutured to it *via* an epineural-epimysial stitch with polypropylene 6-0/ 8-0 or (2) directly sutured to recipient motor nerve branches by an end-to-end epineurial coaptation with polypropylene 6-0/ 8-0 [18,26].

Results

Demographics

Ten traumatic amputees from North Africa and the Middle East were included. Nine were men and one was a woman. The average age was 25.9 years (range: 17 to 36 years). The cohort suffered the following amputation-levels: Three above-knee, one forefoot, one

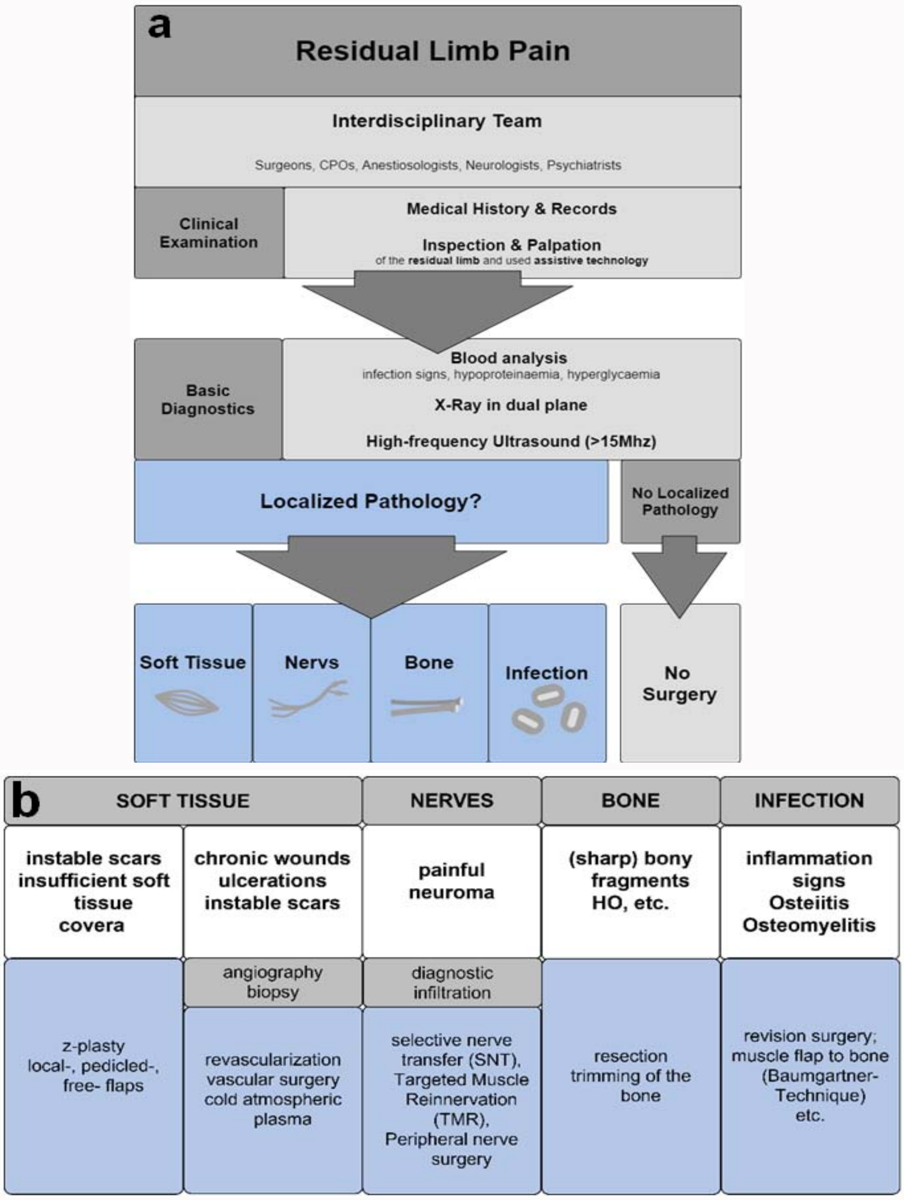

Figure 1: a) Algorithm which serves as worksheet of the interprofessional "Interdisciplinary Amputee Outpatient Clinic". The evaluation starts with a physical examination by an interprofessional team of an orthopedic surgeon, plastic surgeon, prosthetist and occupational therapist. If needed a neurologist and pain therapist were involved. Recorded were conditions of amputation- past medical history and past treatment followed inspection and palpation of the residual limb for localizing the pain sites and identification of neuromas (Hoffmanns Tinel's sign) insufficient or excessive soft tissue coverage and painful scars. Prosthetic alignment, socket suspension, pharmaceutical and non-pharmaceutical pain treatment were reevaluated. After physical examination, diagnostic followed: Dual-plane x-ray of the residual limb in dual-plane to localize and identify bony fragments or foreign bodies; high-resolution ultrasound image neuroma if the physical examination confirmed positive Hofmann-Tinel´s sign. In case of positive medical history and clinical signs for infection diagnostics included blood analyze and additional imaging (MRI, CT-Scans). b) If the algorithm reveals a or a combination of localized pathology as soft tissue complications, nerves, bones or an infection- (surgical) interventions including revision surgery following surgical principles and the reconstructive ladder (highlighted in light blue) should address the target to relieve pain (Ernst et al., 2017).

partial hand, three transradial, and two transhumeral amputee.

Nine patients were unilateral, one quadruple amputee. One transradial amputee suffered an additional contracture proximally to the residual limb- at the elbow joint -which was revised within revision surgery.

Nine patients lost their extremity related to war injuries (blasting injuries), one due to a high-voltage injury. During the observation time two cases healed by controlled secondary wound healing (Figure 3), one needed re-revision surgery.

Seven amputees were revised because of amputation-related pain or complications at the residual limb prohibiting prosthetic fitting after non-invasive treatment options were exhausted and the algorithm identified a pathology, the remaining two amputees as the characteristics of their residual limb did not allow socket and prosthetic fitting (Table 1 and Figures 4-9).

Pain at the RL

After revision surgery, there were significant changes of the pain level. The mean numeric rating scale score of the preoperative pain level was 8.1 (range: 7 to 10) and was significantly reduced to 1.7 (range: 0 to 3; $p < 0.05$) after revision surgery. Three amputees were revised because of poor soft tissue conditions at the residual limb

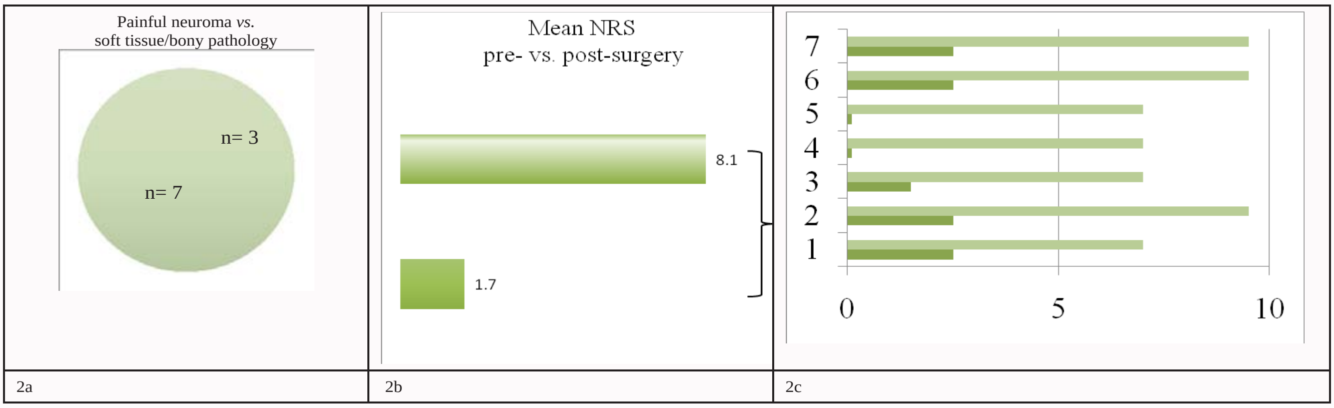

Figure 2: a) The ratio of painful neuromas at the residual limb (light grey) versus soft tissue and bony pathology (dark grey) is according to literature. b) Means of the pre- (light grey) and postoperative (dark grey) pain level (NRS, 0-10) of patient #1-7. c) The graph indicates of pre- (light grey) and postoperative (dark grey) pain level (NRS, 0-10) of patient #1-7, individual.

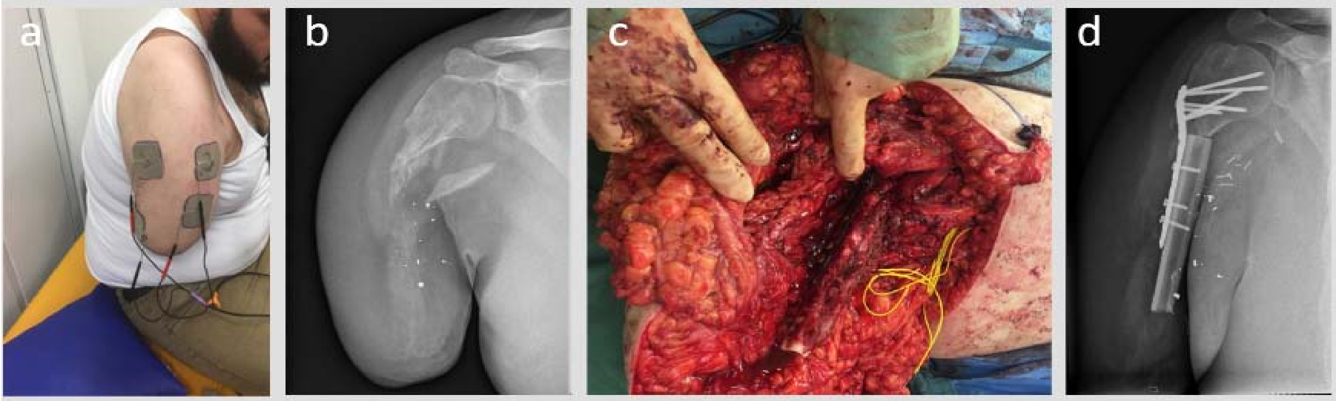

Figure 3: a) No EMg signal could be measured at the long transhumeral residual limb. The x-ray revealed the missing lever arm, meaning the humerus-bone. b) A free-vascularized fibula from the ipsilateral leg was transferred and SNT for TMR: the ulnar nerve to medial biceps head. To our knowledge he was revised and infected fibula removed. Retrospectively, two errors occurred: Neurophysiological examination with needle EMG showed muscle activity and no pathological spontaneous activity therefore we did not perform MRI scans. Intraoperatively, we were surprised. c): there were limited remaining muscle belly of the medial biceps, and the coracobrachialis-muscle. d) Furthermore, swabs should have been taken before fibula transfer, as the 4-MRGN was still present in the healed residual limb, and finally infecting the transplant. Complications occurred as algorithm wasn't followed strictly.

avoiding sufficient socket suspension (Figures 2a-2c).

Pathologies and complications at the RL

Seven patients suffered a painful neuroma, three inefficient soft tissue coverage of the RL (two insufficient, one excessive). In six patients the surgery removed foreign bodies related from the battlefield or calcifications of soft tissue resulting from the high energy of the trauma (Table 1 and Figures 4-9).

The surgical techniques

Following surgical techniques were used to reshape the residual limb: Scar excision, local and free flaps, Baumgartner's myoplasty. Free Fibula transfer, k-wire arthrodesis were used for bone reconstruction. HO fragments and foreign bodies were removed and the remaining boned smoothened (Table 1 and Figures 4-9).

Prosthetic rehabilitation

Nine out of ten patients immediately started prosthetic fitting as soon as the wound was fully healed, and the k-wire arthrodesis was healed and k-wires removed. Within the observation time of 12 months there was no recurrence of pain, tender points, impaired socket suspension limiting prosthetic fitting.

For eight out of ten patients revision surgery enabled prosthetic fitting which was not previously possible. One patient returned to his home-country before fitting was finished. A second patient wanted to return home for reinnervation process. To our knowledge the patient was revised due to infection (Table 1).

Discussion

Surgery for pain and complications at the residual limb?

Chronic pain after amputation is often dealt with treating dominantly the symptoms. Pain medications tend to be the first line of treatment when patients complain about pain at the residual limb. Pharmacologic treatments do not serve as a curative treatment for residual limb pain, but merely mask the pain.

Holistic amputee care demands medical and technical knowledge. The clinical examination should be performed by a multi-professional team providing surgical, drug-, (physio-) therapeutical and technical knowledge. It is important to explore and evaluate the range of conservative treatments thereby avoiding to subjecting a patient to unnecessary surgical procedures and related risks. However, once these modalities have been exhausted, revision surgery for the treatment of pain at the residual limb should

Table 1: Showing demographics of the cohort, the pre- and postoperative pain level (NRS), the identified pathology targeted by revision surgery and the following prosthetic fitting.

Patient				NRS		Level of amputation	Localized pathology	Surgical Strategy & Rehabilitation	
	sex	age	mechanism	pre	post			surgical technique	fitted prosthetic device
1	m	31	blast	7	2.5	TH	scar painful neuroma	Scar correction SNT to medical biceps muscle	mechatronic elbow (Dynamic Arm) myo hand (VariPlus Speed)
2	f	17	blast	9.5	2.5	TR	painful neuroma	SNT to flexor muscles forearm	silicone cosmesis, myo hand (VariPlus Speed)
3	m	29	blast	7	1.5	TF	bony fragment medial painful neuroma	Resection bony fragment SNT to thigh muscle Reshaping residual limb	MPK: Genium X3
4	m	28	blast	7	0	TF	“dog ears” painful neuroma	SNT to thigh muscle Reshaping residual limb	MPK: Genium X3
5	m	26	blast	7	0.5	TR	painful neuroma	SNT ulnar nerve to nervus interosseus anterior (branch to pronator quadratus muscle, TMR)	silicone cosmesis myo hand (VariPlus Speed)
6	m	36	blast	9.5	2.5	TF	scar length and soft tissue coverage of TF residual limb	scar correction reshaping of the residual limb Baumgartner myoplasty	MPK: Genium X3
7	m	26	blast	9.5	2.5	FF	instable scar FF, ulcers	free gracilis flap skin mesh graft, donor site thigh	silicone cosmesis FF-
8	m	22	blast	0	0	PH	incomplete fracture healing with deviation dig. III neuroma sensory branch palmar middle hand instable scar proximal forearm and l elbow	k-wire arthrodesis dig. III scar resection& z-plasty forearm resection of neuroma at palmar middle hand SNT into deep palmar hand muscle	silicone cosmesis PH
9	m	30	blast	0	0	TH	excessive soft tissue no humerus bone serving as lever arm, no EMG- signals	free-vascularized fibula transfer SNT: ulnar nerve to medial biceps head serving as myosignal (TMR)	• pending *secondary wound healing
10*	m	24	high voltage	0	0	TR	calcification triceps tendon scar contracture due to mesh graft at medial elbow joint	resection calcification z-plasty triceps tendon; resection skin mesh graft, local flap for tissue coverage	• pending *secondary wound healing, required re-revision

M: Masculine; f: Feminine; NRS: Numeric Rating Scale; Th: Transhumeral; TR: Transradial; TF: Transfemoral; FF: Forefoot; PH: Partial Hand; SNT: Selective Nerve Transfer; MPK: Microprocessor-Controlled Knee

be considered, if there was found a clear and consistent pathology. So far, little attention has been given to the role of revision surgery as a treatment option [5,6,11-14].

If a pathology is identified which can be addressed by surgery, pain can substantially be relieved. Surgery is especially important to consider if neuroma pain is present at the residual limb. Excision transposition and SNT of a painful neuroma can improve the prosthetic fitting, decrease pain and increase mobility [11]. Still, treating chronic pain effectively remains challenging because the presence of chronic pain can result in further psychological disorders and compensatory movements limiting function [5,6,12,13].

The value of the reconstructive ladder for revision surgery

In the decision-making process for surgical techniques validated principles such as described by the reconstructive ladder should be followed [21,22]. Following those principles, the most appropriate and the least complex level of reconstruction is selected which ensures short wound healing time, short immobilisation and faster rehabilitation time to avoid muscle atrophy and contractures.

For the decision making processes and since treatment failure is possible, the algorithm (Figure 1) helps to select patient groups that will benefit from surgical treatment. The core goal is to identify and localize a pathology which can be addressed by the surgery. The algorithm helps the clinicians in patient selection, to choose the right treatment concept and reduce the number of misdiagnoses. In Figure 3 the history of infection with multi-resistant bacteria should have demanded swabs before free fibula transfer to avoid the resulting infection of the transplant. Diffuse pain and inconsistent pain qualities and location should be reevaluated after additional non-invasive therapies. Furthermore, the patient-specific prognostic factors need to be considered.

The elevator in this cohort study is the selective nerve transfer of neuroma at the RL.

A variety of surgical methods have been described for the treatment of painful neuromas including centrocentral anastomosis, excision with coagulation of nerve tip, and silicone capping other

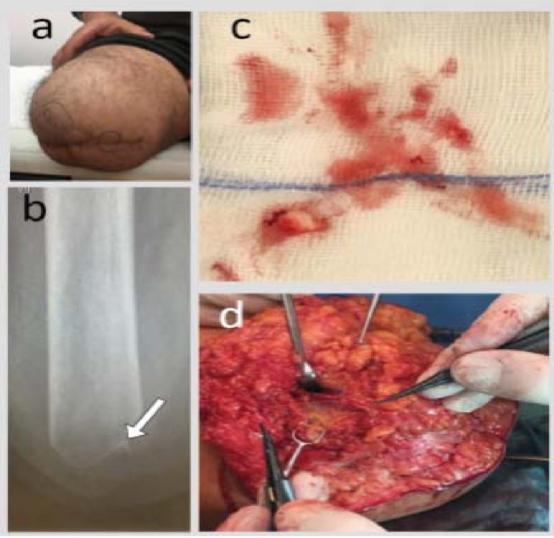

Figure 4: Patient 5 TF Amputee, NRS 7. The algorithm revealed a positive HT-sign ventrally and a bony fragment medially (a), X-ray confirmed the bone fragment (arrow) (b). Fragment was removed (c) and the neuroma transferred to deep recipient nerve (forceps, right) (d) reducing pain level to NRS 1.5.

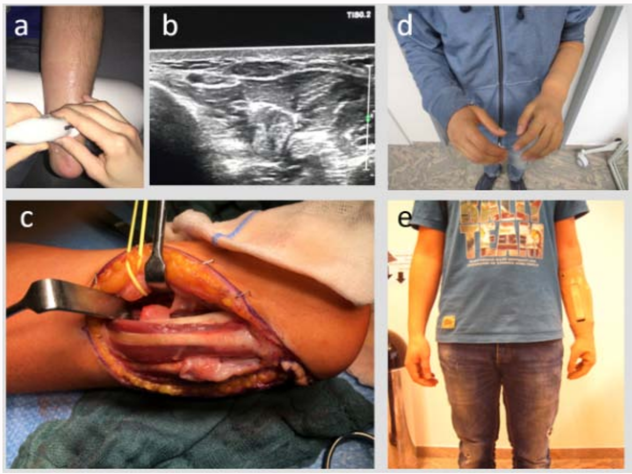

Figure 6: Patient 3, TR Amputee NRS 7; the algorithm revealed a painful neuroma of the ulnar nerve which could be visualized by ultrasound and measured a diameter of 37 mm (a,b); SNT of the ulnar nerve to nervus interosseous anterior (branch to pronator quadrates muscle) reduced allodynia at the residual limb to NRS 0.5 (c); patient could then tolerate socket and was fitted to two channel myoprosthesis and Silicone cosmesis (d,e).

methods that have been described to prevent regrowth of a neuroma include burying techniques of the proximal end of the nerve into tissue to stop neuroma growth. Examples include burying the nerve into bone, vein, or muscle [18,27,28]. In 1959, Munro and Mallory reported success by crushing the end of an amputation stump neuroma and burying the proximal end of the nerve into muscle.

Some of the earliest reports of neuroma treatment report nerve implantation into muscle [29]. He described resection of the neuroma and suturing it into an opening of muscle [18]. Many surgeons have used this muscle-burying technique of resection and muscle implantation with great success. Few methods have been used to specifically treat amputation neuromas to relieve chronic pain. Regarding the application of this technique in amputees, we are aware of only one similar reported case series before [11]. One randomized control trial compared burying the nerve into a muscle to a selective nerve transfer (SNT) in upper and lower limb revision surgery. The SNT led to a reduction of PLP and tented to a reduction of RLP.

In revision surgery it is important to recognize that previous surgical treatments can alter the anatomical location of the neuroma at the residual limb. Familiarity with these situations and the variable anatomy after combat- related amputations is necessary for a successful outcome.

Additionally, a combination of pathologies- as in our cohort study- is needed to be targeted by a combination of surgical procedures to relieve the overall pain level and to solve the complications in prosthetic fitting and rehabilitation. This holistic approach is in concordance to the results of the above named randomized controlled trial. Therein, the failure to reach statistical

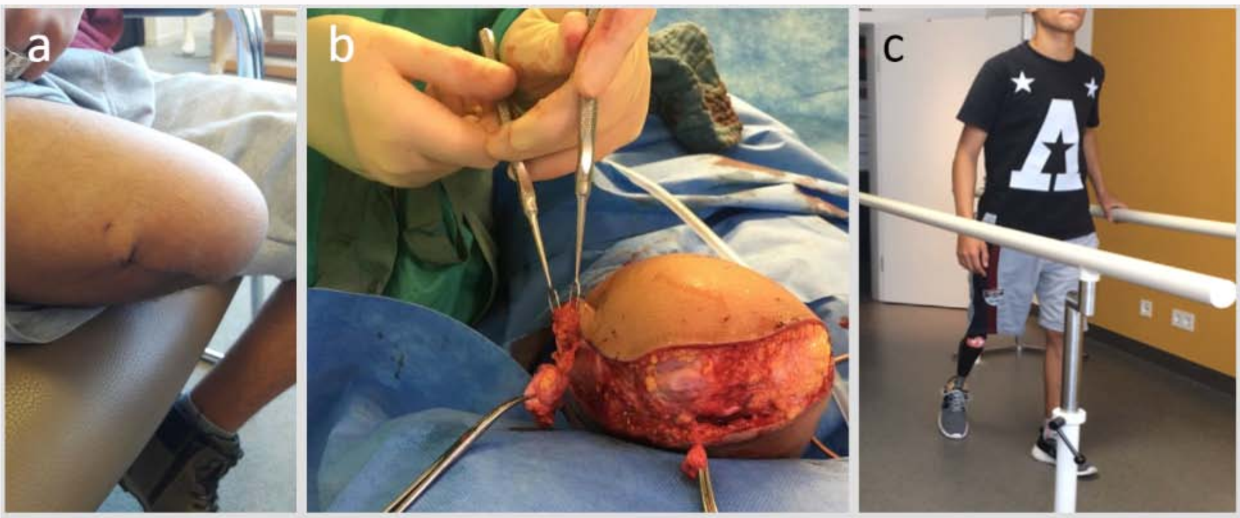

Figure 5: Patient 4 TF, the dog ears was bothering, pain was evaluated with NRS 7 (a). Intraoperatively, a neuroma of lateral cutaneous femoris nerve was damasked, during the dog ear was corrected a neuroma was found at dorsal preparation at the RL. To follow the reconstructive ladder and to keep the surgery as simple as possible, just the fascia was opened an both neuromas sutured on the epimysium of deep muscles (b). The pain was completely resolved NRS 0 and the young patient fitted to a MPK.

Figure 7: Patient 6 TF, NRS 9.5: (a) Short transfemoral residual limb; the inverted scar caused accumulation of sweat in the socket and blisters (b). The revision combined following surgical techniques: Scar correction for reshaping and coverage of the femur by Baumgartner myoplasty (c) and reduced the pain to NRS 2.5.

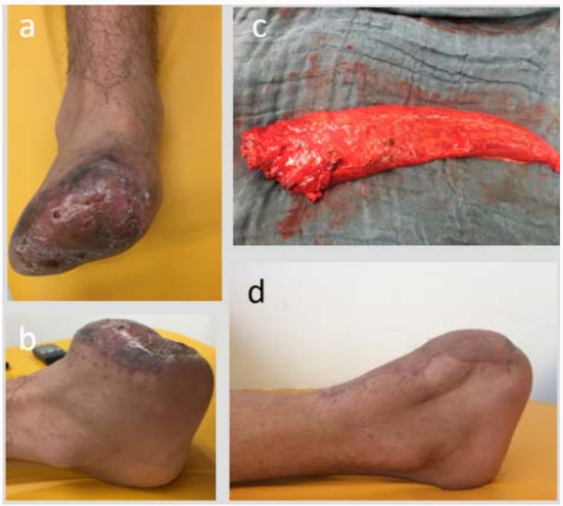

Figure 8: Patient 7, FF, NRS 9.5, covered with a mesh graft scar fragile to pressure caused by the FF-Silicone prosthesis and leading to an instable (a,b). A free gracilis-muscle-flap (c) with skin mesh graft, donor site thigh improved the soft tissue coverage (d) and reduced the pain from NRS 9.5 to 2.5. To shape the muscle flap and smoothen the meshed skin graft we worked with individualized compression garments.

significance with a solely SNT can be mainly explained by the fact that residual limb pain is often not only caused by a single pathology at the residual limb, as e.g. neuromas, but more by a combination of pathologies as bone spurs, ischemia, and further other conditions [11,15].

Limitations

In addition to the low number of analyzed amputees, the cohort was very heterogenous regarding amputation level. An additional weakness of this study is the missing differentiation between RLP from PLP which was rather difficult due to the language barriers, loss of sense in translation and the cultural background and acceptance of PLP.

Conclusion

Revision surgeries including microsurgical techniques have a value in the treatment of postamputation pain and amputation-related complications. After conservative treatment methods have been exhausted, an algorithm considering the reconstructive ladder

Figure 9: Patient 8, PH. Prosthetic fitting with silicone prosthesis for dig. IV +V was not possible because of the deviation of dig III (a,b) after incomplete fracture of dig. III (c). Algorithm revealed furthermore a neuroma of a sensory had nerve-branch at palmar middle hand instable scar proximal medial forearm and medial elbow. K-wire arthrodesis of the proximal interphalangeal joint at dig. II, a resection of neuroma at palmar middle hand buried into deep muscle and a scar resection and z-plasty forearm was performed to target the pathologies enable prosthetic fitting.

seems to direct surgical methods to appropriate targets at the residual limb enabling prosthetic fitting and successful rehabilitation of the amputee.

References

1. Tintle SM, Forsberg JA, Keeling JJ, Shawen SB, Potter BK. Lower extremity combat-related amputations. J Surg Orthop Adv. 2010;19(1):35-43.
2. Andersen RC, D'Alleyrand JCG, Swiontkowski MF, Ficke JR; Extremity War Injuries VIII Session Moderators. Extremity War Injuries VIII: Sequelae of combat injuries. J Am Acad Orthop Surg. 2014;22(1):57-62.
3. Buchheit T, de Ven TV, Hsia HLJ, McDuffie M, MacLeod DB, White W, et al. Pain phenotypes and associated clinical risk factors following traumatic amputation: Results from Veterans Integrated Pain Evaluation Research (VIPER). Pain Med. 2016;17(1):149-61.
4. Ephraim PL, Wegener ST, MacKenzie EJ, Dillingham TR, Pezzin LE. Phantom pain, residual limb pain, and back pain in amputees: Results of a national survey. Arch Phys Med Rehabil. 2005;86(10):1910-9.
5. Jackson MA, Simpson KH. Pain after amputation. Continuing Education in Anaesthesia, Critical Care & Pain. 2004;4(1):20-23.
6. Flor H. Phantom-limb pain: Characteristics, causes, and treatment. Lancet Neurol. 2002;1(3):182-9.
7. Dettmers C, Adler T, Rzanny R, van Schayck R, Gaser C, Weiss T, et al.

Increased excitability in the primary motor cortex and supplementary motor area in patients with phantom limb pain after upper limb amputation. Neurosci Lett. 2001;307(2):109-12.

8. Ramachandran VS, Hirstein W. The perception of phantom limbs. The DO Hebb lecture. Brain. 1998;121(Pt 9):1603-30.

9. Weiss SA, Lindell B. Phantom limb pain and etiology of amputation in unilateral lower extremity amputees. J Pain Symptom Manage. 1996;11(1):3-17.

10. Nikolajsen L, Christensen KF. Phantom limb pain. In Nerves and Nerve Injuries. 2015;23-34.

11. Souza JM, Cheesborough JE, Ko JH, Cho MS, Kuiken TA, Dumanian GA. Targeted muscle reinnervation: A novel approach to postamputation neuroma pain. Clin Orthop Relat Res. 2014;472(10):2984-90.

12. Jensen TS, Krebs B, Nielsen J, Rasmussen P. Phantom limb, phantom pain, and stump pain in amputees during the first months following limb amputation. Pain. 1983;17(3):243-56.

13. Jensen TS, Krebs B, Nielsen J, Rasmussen P. Immediate and long term phantom pain in amputees: Incidence-clinical characteristics in relationship to pre-amputation limb pain. Pain. 1985;21(3):267-78.

14. Sherman RA, Sherman CJ, Parker L. Chronic phantom and stump pain among American veterans: Results of a survey. Pain. 1984;18(1):83-95.

15. Clarke C, Lindsay DR, Pyati S, Buchheit T. Residual limb pain is not a diagnosis: A proposed algorithm to classify postamputation pain. Clin J Pain. 2013;29(6):551-62.

16. Ducic I, Mesbahi AN, Attinger CE, Graw K. The role of peripheral nerve surgery in the treatment of chronic pain associated with amputation stumps. Plast Reconstr Surg. 2008;121(3):908-14.

17. Kretschmer T, Happel LT, England JD, Nguyen DH, Tiel RL, Beuerman RW, et al. Clinical article accumulation of PN1 and PN3 sodium channels in painful human neuroma-evidence from immunocytochemistry. Acta Neurochirurgica. 2002;144(8):803-10.

18. Dellon AL, Mackinnon SE. Treatment of the painful neuroma by neuroma resection and muscle implantation. Plast Reconstr Surg. 1986;77(3):427-38.

19. Kuiken TA, Li G, Lock BA, Lipschutz RD, Miller LA, Stubblefield KA, et al. Targeted muscle reinnervation for real-time myoelectric control of multifunction artificial arms. JAMA. 2009;301(6):619-28.

20. Aszmann OC, Dietl H, Frey M. [Selective nerve transfers to improve the control of myoelectrical arm prostheses]. Handchir Mikrochir Plast Chir. 2008;40(1):60-5.

21. Mathes SJ, Nahai F. Clinical applications for muscle and musculocutaneous flaps. St. Louis, MO: C.V. Mosby; 1982.

22. Gottlieb LJ, Krieger LM. From the reconstructive ladder to the reconstructive elevator. Plast Reconstr Surg. 1994;93(7):1503-4.

23. Baumgartner R. [Upper leg amputation Transfemoral amputation]. Oper Orthop Traumatol. 2011;23(4):296-305.

24. Gottschalk F. The importance of soft tissue stabilization in trans-femoral amputation: English version. Orthopade. 2016;45(Suppl 1):S1-4.

25. Geertzen JHB, van der Schans SM, Jutte PC, Kraeima J, Otten E, Dekker R. Myodesis or myoplasty in trans-femoral amputations. What is the best option? An explorative study. Med Hypotheses. 2019;124:7-12.

26. Kuiken TA, Miller LA, Lipschutz RD, Lock BA, Stubblefield K, Marasco PD, et al. Targeted reinnervation for enhanced prosthetic arm function in a woman with a proximal amputation: A case study. Lancet. 2007;369(9559):371-80.

27. Eberlin KR, Ducic I. Surgical algorithm for neuroma management: A changing treatment paradigm. Plast Reconstr Surg Glob Open. 2018;6(10):e1952.

28. Poppler LH, Parikh RP, Bichanich MJ, Rebehn K, Bettlach CR, Mackinnon SE, et al. Surgical interventions for the treatment of painful neuroma: A comparative meta-analysis. Pain. 2018;159(2):214-23.

29. Moszkowicz L. Zur behandlung der schmerzhaften neurome. Zentralbl Chir. 1918;45:547.