Algorithm for bionic hand reconstruction in patients with global brachial plexopathies

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OBJECTIVE Global brachial plexus lesions with multiple root avulsions are among the most severe nerve injuries, leading to lifelong disability. Fortunately, in most cases primary and secondary reconstructions provide a stable shoulder and restore sufficient arm function. Restoration of biological hand function, however, remains a reconstructive goal that is difficult to reach. The recently introduced concept of bionic reconstruction overcomes biological limitations of classic reconstructive surgery to restore hand function by combining selective nerve and muscle transfers with elective amputation of the functionless hand and its replacement with a prosthetic device. The authors present their treatment algorithm for bionic hand reconstruction and report on the management and long-term functional outcomes of patients with global brachial plexopathies who have undergone this innovative treatment.

METHODS Thirty-four patients with posttraumatic global brachial plexopathies leading to loss of hand function consulted the Center for Advanced Restoration of Extremity Function between 2011 and 2015. Of these patients, 16 (47%) qualified for bionic reconstruction due to lack of treatment alternatives. The treatment algorithm included progressive steps with the intent of improving the biotechnological interface to allow optimal prosthetic hand replacement. In 5 patients, final functional outcome measurements were obtained with the Action Arm Research Test (ARAT), the Southampton Hand Assessment Procedure (SHAP), and the Disabilities of the Arm, Shoulder, and Hand (DASH) questionnaire.

RESULTS In all 5 patients who completed functional assessments, partial hand function was restored with bionic reconstruction. ARAT scores improved from 3.4 ± 4.3 to 25.4 ± 12.7 ($p = 0.043$; mean $\pm$ SD) and SHAP scores improved from 10.0 ± 1.6 to 55 ± 19.7 ($p = 0.042$). DASH scores decreased from 57.9 ± 20.6 to 32 ± 28.6 ($p = 0.042$), indicating decreased disability.

CONCLUSIONS The authors present an algorithm for bionic reconstruction leading to useful hand function in patients who lack biological treatment alternatives for a stiff, functionless, and insensate hand resulting from global brachial plexopathies.

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KEY WORDS prosthetic replacement; brachial plexus injury; elective amputation; prosthetic rehabilitation; peripheral nerve

INJURIES to the brachial plexus (BP) that include avulsion of nerve roots may result in upper-limb paralysis and loss of hand function. High-speed motor vehicle accidents account for the vast majority of BP lesions,¹⁹ which most commonly affect young adults in the prime of life.^{9,11} After the occurrence of whiplash injuries of the neck and arm region, high-energy traction on single nerve fascicles is the most frequently observed mechanism of

injury.^{12,32} Paralysis of the upper limb following global plexopathies is tremendously disabling, both physically and socially,¹⁰ often leading to severe therapy-resistant pain as well as unemployment, decreased self-sufficiency, and social-emotional consequences of poor body image.¹⁸

Thus, in addition to standard trauma management, treatment of this complex nerve injury should be initiated as soon as possible. In patients with multiple root avul-

ABBREVIATIONS ADL = activities of daily living; ARAT = Action Research Arm Test; BP, BPI = brachial plexus, BP injury; DASH = Disabilities of the Arm, Shoulder, and Hand; EMG, sEMG = electromyographic, surface EMG; FFMT = free functional muscle transplantation; SHAP = Southampton Hand Assessment Procedure; VAS = visual analog scale.

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sions, repair has been focused on restoration of shoulder stability and biceps function.^{35,36,38} If the lower roots are avulsed, however, the return of hand function is hardly ever achieved due to limited axonal support, long denervation time of muscles located more distally, and accompanying joint stiffness. Even though bodily integrity is maintained, some patients refer to their hand as an insensate, useless appendage that they would rather have amputated.¹⁴

Patients with BP lesions who seek treatment at our center sometimes do so a long time after their accident. Most of these patients have received appropriate primary surgical management but nevertheless are left with inadequate or poor distal function, and some patients suffer tremendous therapy-resistant deafferentation pain. In such cases we have recently applied a new technique that overcomes the biological limitations of classic reconstructive surgery to restore hand function. This innovative approach, called bionic reconstruction, combines selective nerve and muscle transfers with elective amputation of the functionless withered hand and its replacement with a prosthetic device.³

Here we present our experience over the last 5 years in managing severe BP injuries (BPIs) with loss of hand and arm function. We present data obtained in a total of 34 patients with global brachial plexopathies treated in a single center. In 16 cases, in which primary and secondary biological reconstructions failed to improve hand function, bionic hand reconstruction was initiated. Final functional outcome measurements are presented for 5 of the 16 patients (with 11 patients still in the process of training prior to prosthetic hand reconstruction). The multidisciplinary approach and underlying treatment algorithm for bionic hand reconstruction is illustrated step by step (ranging from identification of eligible patients to final prosthetic hand replacement). Additionally, the effect of bionic hand reconstruction on deafferentation pain is addressed.

Methods

Patient and Demographic Data

Between 2011 and 2015, a total of 34 patients with posttraumatic global brachial plexopathies consulted our Center for Advanced Restoration of Extremity Function. In 65% of the patients motorcycle accidents accounted for the BPI (Table 1). In 18 patients (53%), primary and secondary BP reconstructions alone restored sufficient hand and arm function. However, in 16 patients (47%) the neurological injury was so severe that distal function could not be achieved with biological means alone and bionic reconstruction was necessary to restore adequate hand function. At the time of this report, 11 patients were still in the process of training prior to prosthetic hand replacement and were excluded from this study. Evaluation of the final outcomes was performed for 5 patients, with a minimum follow-up of 3 months after final prosthetic fitting. The follow-up duration was 10 ± 7 months (mean $\pm$ SD) (range 3–17 months). All 5 patients were male. Patient age at time of prosthetic fitting was 38.1 ± 11.6 years (range 26.8–57.2 years). The average period between BPI and initial consultation at our institution was 7 ± 5.8 years (range 1.3–14.9 years).

TABLE 1. Type of accident for 34 patients with posttraumatic BPIs

Type of Accident	No. of Patients (%)
Motorcycle	22 (64.71)
Bicycle	6 (17.65)
Work related	2 (5.88)
Fall from height	1 (2.94)
Skiing	1 (2.94)
Pedestrian	1 (2.94)
Other motor vehicle	1 (2.94)

Avulsion of at least 2 nerve roots was present in 4 of 5 patients (80%) (Table 2). In all 5 patients, primary BP reconstruction was done long before the assessment for bionic reconstruction, but surgical outcomes showed negligible hand function. Failure of all previously attempted biological reconstruction procedures was the primary indication for inclusion in this study.

Ethics approval was obtained from the local institutional review board. All patients gave written informed consent.

Algorithm for Bionic Hand Reconstruction

The algorithm for bionic hand reconstruction in patients with global brachial plexopathies is displayed in Fig. 1.

Initial Review

Examination of the patient at initial review involved an interdisciplinary team including plastic surgeons, physiatrists, physiotherapists, prosthetists, and a clinical psychologist. A comprehensive case history included review of all records on previous reconstructive surgeries (including nerve transfers and grafts, free functional muscle transplantations [FFMTs], and other procedures), a detailed musculoskeletal assessment of hand/arm function and, if needed, high-resolution ultrasound, MRI, and nerve conduction studies to assess the state of existing muscles and nerves.

In cases of complete hand paralysis, absent sensation, and lack of treatment alternatives, the next step in the algorithm was to identify electromyographic (EMG) signals generated by muscles in the forearm that would be available for control of a prosthetic device.

Identification of EMG Signals

Following global brachial plexopathies that include multiple avulsions of nerve roots, hand function can be negligible. However, there may still be detectable muscle activity without clinical significance (M1 according to the British Medical Research Council scale) that can be identified with transcutaneous electrodes. Therefore, during consultation we aimed to find surface EMG (sEMG) hotspots; i.e., positions on the patient's skin where a (relatively) high sEMG amplitude can be detected. Biofeedback was initiated, using muscular activity and EMG signal amplitudes that were visualized on a computer screen and simultaneously translated into prosthetic function

TABLE 2. Type of accident, lesion, and timely primary reconstructive surgeries performed before initial consultation at our institution

Case No.	Type of Accident	Type of Lesion	Primary Reconstructive Surgeries Aimed at Restoration of Shoulder & Elbow Function
1	Fall from height	Avulsion of C7–T1, stretch traction injury of the remaining infraclavicular plexus	Reinnervation of forearm flexors was attempted using the brachialis muscle branch of the MCN to medial cord of the MN; after motor recovery was unable to move the biological hand (op performed 4 mos after injury)
2	Skiing	Avulsion of C6–T1	Restoration of shoulder stability & elbow function was achieved using a vascularized ulnar nerve graft to axillary nerve & MCN, transfer of the 4th ICN to MCN, and transfer of accessory nerve to suprascapular nerve (op performed 10 mos after injury)
3	Motorcycle	Avulsion of C8–T1, rupture of C5–7	Sural nerve grafts were used to bridge defect of C5–7 to restore elbow flexion & shoulder stability (op performed 3 mos after injury)
4	Motorcycle	Rupture of all 3 trunci	Restoration of shoulder stability & elbow function was achieved using a sural nerve graft from C-5 to MCN, a sural nerve graft from C-6 to axillary nerve, a sural nerve graft from C-6 to lat cord of the MN, & a contralat medial antebrachial cutaneous nerve graft to radial nerve (op performed 7 mos after injury)
5	Motorcycle	Avulsion of C8–T1, massive nerve crush injuries at infraclavicular space	Restoration of shoulder stability, elbow function, & wrist extension was achieved by neurolysis of posterior cord, sural nerve grafts from lat cord to MCN & MN, & sural nerve grafts from medial cord to MN & ulnar nerve (op performed 3 mos after injury)

ICN = intercostal nerve; MCN = musculocutaneous nerve; MN = median nerve.

with a tabletop prosthesis mounted in front of the patient. This approach allowed us to predict prosthetic hand function that could be expected after bionic reconstruction.

To govern a myoelectric prosthesis, at least 2 cognitively separate EMG signals are needed.³¹ These 2 signals control the prosthesis linearly, and co-contraction can be used to switch between different functional levels (wrist and hand) of the prosthetic device. Depending on the remaining myoactivity, 2 further distinct steps emerged in the treatment algorithm, as follows. 1) In case of at least 2 sufficient EMG signals the patient was provided with further training to optimize signal consistency and separation before amputation and prosthetic hand replacement. Three patients presented with at least 2 identifiable EMG signals in the forearm during initial consultation. 2) If the patient was only able to actively target 1 muscle, selective nerve transfer in combination with FFMT was performed to create a new EMG signal site. This was performed in the remaining 2 patients.

Selective Nerve Transfer

During clinical examination a positive Tinel sign indicated the presence of live axons within nerves of the forearm and upper arm; however, surgical exploration of the BP was indispensable to evaluate residual nerve function by using intraoperative nerve stimulation. Following long denervation intervals, however, muscles might not show adequate response to nerve stimulation. For that purpose acetylcholine positivity was assessed to determine motor axons and their intraneural topography, to be used for reinnervating a new target muscle. In some of the patients an FFMT was performed with the intent of restoring function in the actual wrist and hand (Case 5). In others the hand was beyond functional rehabilitation, and the muscle transfer was done a priori to create a signal site for future prosthetic control (Case 4).

Rehabilitation Following Surgery and EMG Signal Training

Subsequent to nerve transfer surgery, patients were fol-

lowed up regularly during a 3-month interval. In the early rehabilitation stage, wound and pain management was initiated. Motor imagery of hand movements was then trained with the aid of a physiotherapist. Additionally, weak muscles of the adjacent joint (e.g., the biceps muscle for a planned transradial amputation) were strengthened. Within 6 months after surgery the first voluntary contractions of the new target muscle could be expected. At this stage of rehabilitation, patients learned how to activate the reinnervated muscle. This cognitive training was supported by EMG biofeedback.

The main goal of the signal training was to teach the patient how to separately activate the 2 EMG signals and how to modulate the amplitude. This was needed later on for fine prosthetic control. In the beginning, activation of one signal without the other was challenging for the patients. Therefore, regular weekly training with biofeedback methods was necessary. Cognitive training was promoted with home training tools visualizing EMG activity and therefore signal intensity. This allowed sufficient training units without the need to see a therapist on a daily basis.

Psychological Evaluation

Psychological evaluation by the team's clinical psychologist was an integral component of the algorithm, consisting of a semistructured interview. The interview was divided into 5 parts: accident, current situation, psychosocial issues, possible amputation, and prosthetic hand replacement. The aim of the interview was first to gain an overview of the present psychosocial circumstances, and second to give insight into the patient's cognitive capability of estimating the consequences of an elective amputation. Mental disorders, such as posttraumatic stress disorders, alcohol or substance abuse, insufficient emotional coping, and expected noncompliance were defined as contraindications for the procedure. In the case of any of the contraindications described above, psychological support was provided.

FIG. 1. Algorithm for bionic hand reconstruction in patients with global brachial plexopathies. The long arrow pointing downward indicates the order of clinical steps of the algorithm. If 2 signals are detected during EMG signal identification, the third step (nerve transfer and/or FFMT) is left out (curved arrow).

Hybrid Hand Fitting

As soon as the patient achieved full control of at least 2 EMG signal sites, objective function tests (Action Research Arm Test [ARAT] and Southampton Hand Assessment Procedure [SHAP]) were performed with a hybrid prosthetic hand, translating this predefined myoelectric activity into prosthetic function. The hybrid hand consists of a splint-like construction with a myoelectric hand prosthesis mounted onto or below the impaired hand (Video 1).

VIDEO 1. Clip showing SHAP testing of the patient in Case 3 at 3 time points: before amputation, with hybrid hand, and after final prosthetic fitting. Copyright Laura A. Hruby. Published with permission. Click here to view.

This setting allowed us to predict prosthetic control prior to amputation, and also gave the patient an idea of prospective prosthetic hand use. Additionally, training for activities of daily living (ADL) was supported with the hybrid hand and, if possible, the prosthesis was used as a home training tool (Fig. 2). The hybrid hand setup was also essential to evaluate residual upper-limb function because shoulder stability and elbow flexion have to be strong enough to lift the prosthesis against resistance. Upper-limb function and overall muscle strength as well as ranges of motion of the elbow and shoulder often improved during training with the hybrid hand. The absence of triceps function was not a contraindication for bionic

reconstruction because gravity provided sufficient elbow extension. Only patients who demonstrated a clear functional benefit with the hybrid hand were considered for amputation.

Elective Amputation

Depending on EMG signal sites and residual sensory function, elective amputation was performed at the transradial level. Depending on the remaining sensation of the arm, the most sensitive skin surface was used for coverage to obtain a fully sensate stump for better prosthetic fitting and feedback.³ Elective amputation was performed at the transradial level 17 cm from the lateral epicondyle to provide an optimal stump length for prosthetic fitting. This length was gauged to make enough room for the different prosthetic components but also to maintain the best possible leverage. Due to preexisting complete atrophy of forearm muscles, prosthetic fitting was possible after 4–6 weeks, as opposed to the time frame for conventional transradial amputees.³¹

Bionic Reconstruction—Final Prosthetic Fitting

As soon as all wounds had healed and no further variations in stump volume were expected, prosthetic fitting was initiated. To optimize prosthetic control in ADL, therapy sessions were highly recommended after the final fitting as well.³³ Final functional assessment was performed at least 3 months after the final prosthetic fitting (performance of SHAP and ARAT with prosthetic hand, and the Disabilities of the Arm, Shoulder, and Hand [DASH] questionnaire).

Statistical Analysis

The results are presented as the percentage, mean, and SD. Functional outcome measurements (ARAT, SHAP, and DASH) used categorical variables. Therefore, a paired 2-tailed Mann-Whitney U-test was used for the analysis. A p value < 0.05 was considered to be significant. The statistical analysis was performed using SPSS 22 (IBM Statistics).

Assessment of Outcomes

Global arm and hand function was assessed using the ARAT, SHAP, and DASH questionnaire. The ARAT, an observational test used to determine upper-limb motor function, consists of 4 sections with different tasks and a maximum of 57 points attainable.²⁵ This test was performed according to the standardized approach reported by Yozbatiran et al.⁴² The SHAP is a clinically validated hand function test originally developed to assess the effectiveness of upper-limb prostheses.²² It consists of tasks involving 6 abstract objects (each with 2 different weights, heavy and light) and 14 activities of daily living (ADL), with each task timed by the participants themselves. Normal hand function is indicated by a score of ≥ 100 points.¹³ Because of limited range of motion of the shoulder joint, patients performed the SHAP while in the standing position. Tasks that require 2 hands in daily life were rated with the DASH, which has been validated for use in patients with musculoskeletal diseases and injuries to the arm. A score of 100 indicates the worst and 0 indicates

FIG. 2. Photograph showing the patient in Case 2 with hybrid hand setup used as a home training tool.

the best hand function.²¹ Testing of global arm function (ARAT and SHAP) was performed at 3 time points: 1) before amputation, with the impaired hand; 2) before amputation, with the hybrid hand setting; and 3) after amputation, at least 3 months (mean 10 months) after the final prosthetic fitting. The DASH was not done with the hybrid device, because the device was not available in the patients' homes (a requirement of the DASH questionnaire).

For documentation of deafferentation pain during initial review (see Algorithm), patients were asked about the presence of deafferentation pain with regard to localization and qualitative pain characteristics (e.g., burning/crushing/pulsatile, and so on). History of pain medication was documented. The patients' pain levels in the hand and arm were assessed with the visual analog scale (VAS), a widely used tool for measuring pain by asking the patient to mark his or her perceived pain intensity with a point along a 10-cm horizontal line, whereby a score of 0 represents no pain and 10 the maximal imaginable pain. The VAS scores were assessed twice: during initial review and at least 3 months after the final prosthetic fitting.

Results

Of a total of 34 patients, 47% (16 patients) presented with a stiff, insensate, and intrinsically functionless hand

TABLE 3. Surface EMG signals at initial review for all 5 patients

Case No.	sEMG Signal Sites at Initial Review	Selective Nerve Transfer &/or FFMT
1	Forearm extensor compartment + pronator teres muscle	ND
2	Forearm extensor compartment + pronator teres muscle	ND
3	Forearm extensor compartment + pronator teres muscle	ND
4	Pronator teres muscle	Free gracilis muscle transferred to forearm extensor compartment & neurotization of deep branch of radial nerve to obturator nerve (op performed 15.3 yrs after injury)
5	Forearm extensor compartment	Free gracilis muscle transferred to forearm flexor compartment & neurotization of brachialis muscle branch of MCN to obturator nerve (op performed 2.6 yrs after injury)

ND = not done.

In Cases 4 and 5, selective nerve transfer and FFMT were necessary to create a second separable EMG signal site for linear prosthetic control.

lacking treatment alternatives and thus qualifying for bionic reconstruction. Five patients were available for long-term functional outcome measurements. In 3 of these patients, at least 2 cognitively separate surface EMG signals were identified during initial review (Cases 1–3). In the remaining 2 patients, a second EMG signal had to be created by means of selective nerve transfer and/or FFMTs. Individual EMG signal sites in all 5 patients are displayed in Table 3. Final functional evaluation was performed at 10 ± 7 months after prosthetic fitting (Table 4).

Prior to reconstruction, the mean ARAT score was 3.4 ± 4.3 . The ARAT scores improved both during intermediary testing with the hybrid hand (11.4 ± 11.3) and after final prosthetic fitting (25.4 ± 12.7 , $p = 0.043$). The mean SHAP score increased from 10 ± 1.6 before to 21.8 ± 4.8 with the hybrid hand and to 55 ± 19.7 ($p = 0.042$) with the final prosthetic hand (Video 1). The mean DASH scores decreased from 57.9 ± 20.6 to 32 ± 28.6 ($p = 0.042$).

Three of 5 patients reported daily moderate to severe deafferentation pain in the deafferented hand and forearm during initial review (Table 5). Three months after final prosthetic fitting, daily prosthetic hand use led to a pain reduction from VAS 8.8 to VAS 2.1 in the patient in Case 1 and from VAS 7.6 to VAS 3.5 in the patient in Case 2. The patient in Case 3 reported a pain reduction of 2 cm on the VAS scale (from VAS 9.5 to VAS 7.5). Required pain medication could be reduced in all patients.

Discussion

Global brachial plexus injuries can lead to a long-

term paralytic flail limb, especially when associated with multiple root avulsions. The number of global brachial plexopathies continues to rise due to the widespread use of motorcycles and the increasing number of survivors of high-speed motor vehicle accidents.^{27,40,41} In our series, 22 of 34 patients were involved in motorcycle accidents.

Following BPI, surgical management and nerve reconstruction should be initiated¹⁵ early to prevent irreversible fibrosis of muscles in the arm and stiffness of joints due to the lack of sufficient neural input.^{35,40} Primary reconstructive techniques include direct neural repair using nerve grafts, as well as intra- and extraplexual nerve transfers.^{10,23} In longstanding lesions with irreversible atrophy of muscles, secondary reconstructive surgeries are performed: FFMTs and arthrodesis, as well as tendon transfers and tenodesis.^{6,8,26,37} Although shoulder stability and elbow function can be expected to be restored in the majority of patients, restoration of hand function remains a reconstructive challenge that is difficult to achieve even if surgery is performed early.³⁹ In late cases, due to muscle fiber degeneration and joint stiffness, only a limited number of secondary reconstructive procedures are available; however, these are often futile in the described patient population.

In 53% of the described cohort of 34 patients, classic reconstructive techniques restored sufficient hand/arm function similar to that reported in the literature.^{37,38} In the remaining 47%, the patients demonstrated dismal hand function attributable to poor or inadequate surgical management or extensive neural injury. For this patient group

TABLE 4. Functional outcome scores assessed with ARAT, SHAP, and DASH

Case No.	ARAT			SHAP			DASH	
	Before	Hybrid	After	Before	Hybrid	After	Before	After
1	7	22	35	8	19	75	25.8	10.0
2	0	0	13	10	24	40	71.7	59.2
3	1	1	22	12	15	39	78.3	65.8
4	0	10	15	9	24	43	51.7	4.2
5	9	24	42	11	27	78	62.0	20.8
Mean $\pm$ SD	3.4 ± 4.3	11.4 ± 11.3	25.4 ± 12.7	10.0 ± 1.6	21.8 ± 4.8	55 ± 19.7	57.9 ± 20.6	32 ± 28.6

In ARAT, a maximum of 57 points is attainable. In SHAP, a score of ≥ 100 points indicates normal hand function. In DASH, a score of 100 indicates the worst and 0 indicates the best hand function.

TABLE 5. Deafferentation pain in the hand and forearm evaluated with VAS and requiring pain medication before (during initial review) and after (3 months after final fitting) bionic hand reconstruction

Case No.	VAS Score		Pain Medication*	
	Before	After	Before	After
1	8.8	2.1	Hydromorphone 16 mg: 2-1-1 Pregabalin 300 mg: 1-1-1 Fentanyl (transdermal): 25 µg every 48 hrs	Pregabalin 150 mg: 1-0-1
2	7.6	3.5	Pregabalin 150 mg: 1-1-1 Fentanyl (transdermal): 75 µg every 48 hrs	Fentanyl (transdermal): 25 µg every 48 hrs
3	9.5	7.5	Tramadol 200 mg: 1-1/2-1 Pregabalin 600 mg: 1-0-1 Amitriptyline 100 mg: 0-0-1	Tramadol 200 mg: 1-0-1 Pregabalin 300 mg: 1-0-1
4	0	0	None	None
5	0	0	None	None

* The hyphenated numbers denote the number of tablets taken by patients in the morning, at lunchtime, and in the evening.

there is currently no known reconstructive technique that can restore useful function to the existing hand, but bionic reconstruction offers an effective alternative, translating faint myoactivity into differentiated prosthetic hand use. The application of this concept has recently been reported for 3 such patients.³ Here we describe the underlying treatment algorithm, providing detailed procedures and operations.

Prerequisites for bionic reconstruction include useful shoulder and elbow function and at least 2 cognitively separate EMG signals in the forearm.³ Internal rotation contractures of the shoulder joint as well as co-contractions of biceps and triceps are common problems facing patients with global plexopathies. Thus, in some of our patients conventional reconstructive surgeries were performed to improve the residual arm function. Humeral derotational osteotomies ($n = 2$) or triceps-to-biceps tendon transfers ($n = 2$) were used to enhance future prosthetic function, because shoulder and elbow function are a prerequisite in positioning and using the myoelectric device in 3D space.³

At initial examination patients were identified in whom other reconstructive efforts were deemed futile, thus qualifying these patients for bionic reconstruction. Only patients with a stiff, insensate, and functionless hand were considered for prosthetic hand replacement. In some, remaining muscle activity could be detected. Although clinically insignificant (M1 on the British Medical Research Council scale), this muscle activity was still more than sufficient to provide a cognitive signal for prosthetic function. Voluntarily accessing this myoactivity often presents a challenge, because the patient may not know exactly how to target this muscle due to aberrant reinnervation and loss of sufficient proprioceptive feedback. Thus, a structured rehabilitation program and signal training must be initiated at this time and are considered integral parts of the algorithm.

In the 3 patients who presented with 2 separable EMG signals at initial review, intense training and cognitive practice resulted in intuitive signal control. In the other 2 patients only 1 EMG signal could be identified in the biological wasteland of the forearm, necessitating a second signal site that was created with a free functional gracilis muscle transplant. To enhance nerve regeneration and

muscle reinnervation, as well as signal consistency and thus reliable future prosthetic control, the patient was offered various biofeedback methods during rehabilitation.³⁴ Myoactivity was visualized on a computer screen and simultaneously translated into prosthetic function with a tabletop prosthesis. Home training tools visualizing EMG activity further enabled patients to optimize signal intensity and modification. Additionally, functional improvement as provided by the hybrid prosthetic hand confirmed the ability to reliably control a prosthetic hand prior to elective amputation.

The functionality of a myoelectric prosthesis can by no means compare with that of a biological hand.²⁰ However, given the poor status of hand function in the patient population presented in our study, excellent prospective prosthetic hand use justifies replacement with a mechatronic device. Even if the bionic hand or arm will always remain an “assist” extremity, bimanual dexterity is an important part of interacting with our daily environment and represents an immense expansion of manual capacity. Furthermore, the prosthetic hand can take over simple tasks that require brute strength, freeing the contralateral hand and arm of the patient for small-object manipulation and touchpad-dependent technology, reflecting a sense of diverse dexterity observed in many other biological scenarios as well.⁵

As displayed in Table 4, there is a deviation in functional outcome measures between the patients in Cases 1 and 5, who showed higher SHAP and ARAT scores compared with the patients in Cases 2 and 3. This discrepancy is due to different time points of functional evaluation. In Cases 2 and 3, final functional outcome was assessed only 3 months after prosthetic fitting, whereas in Cases 1 and 5 it was evaluated 11 and 17 months after prosthetic fitting, respectively. Therefore, an increase in SHAP and ARAT scores is also expected to occur in Cases 2 and 3 within months to a year or more of daily prosthetic hand use.

In all 5 patients, impaired hand function, poor body image, and chronic pain following deafferentation led to great psychological distress, resulting in high absence rates from social activity due to sickness, unemployment, and withdrawal from social interaction. In the context of body image, our results demonstrate that the reconstructed

arm and hand was integrated into the patients' body image. This was reflected by high wearing rates (up to 14 hours during work days and weekends) as well as personal statements when we asked patients about their relationship to the new hand.

Following avulsion injury, the development of a chronic pain syndrome, referred to as deafferentation pain, is a very common sequel. Deafferentation pain is thought to arise secondary to deafferentation of neurons and scar formation located in the superficial Rexed layers of the dorsal horn.⁴ Because this pain syndrome includes constant background pain as well as seizure-like episodes,^{1,7} it is widely known to cause major psychological harm as well as social withdrawal in affected patients.

In all 3 patients who reported severe deafferentation pain preinterventionally, prosthetic hand replacement led to pain relief as a consequence of functional reafferentation and replacement of the phantom limb with a prosthetic hand.²⁴ Patients reported a subjectively observed correlation between daily wearing time of the prosthesis and pain reduction. Thus, when the prosthetic device could not be worn due to regular maintenance, pain was reported to increase again within days.

Whereas the patients in Cases 1 and 2 benefited dramatically from prosthetic hand replacement and reported major pain relief (VAS scores decreased from 8.8 to 2.1, and from 7.6 to 3.5, respectively), the patient in Case 3 reported a pain reduction of only 2 cm on the VAS scale, which constitutes the smallest clinically relevant change.²⁸ This specific patient was not able to wear his prosthesis on a regular basis during evaluation 3 months after final fitting, because logistic problems were encountered with local orthopedic technicians in the patient's hometown in Italy. With future daily prosthetic hand use and regular, increased wearing times, we also expect a more clinically relevant pain reduction in this patient.

Future Perspective

Upcoming technological developments will have great impact on signal processing and uptake for myoelectric control; therefore, indications and further clinical use of bionic reconstruction will extend within the coming years.^{16,17,30} Because the number of signal sites and the myoelectric activity of these muscles are limited in the described patient population, pattern recognition or regression algorithms may not be used as is done for conventional amputees. Still, these systems may be able to extract more information on the existing faint muscle signals and therefore improve prosthetic function. Additionally, implantable electrodes will enhance EMG uptake and provide consistent high-quality signals independent from skin texture or transpiration, subcutaneous fat, or prosthetic socket movements.²⁹ Finally, sensation and tactile prosthetic feedback, which are important for differentiated manual tasking, may also be realized in future prosthetic systems.^{2,16}

Conclusions

In patients with global brachial plexopathies, reconstruction has been focused on shoulder stability and el-

bow function. Restoration of hand function, however, remains the most difficult challenge. Bionic reconstruction overcomes biological limitations of classic reconstructive approaches and successfully enables hand function with prosthetic means. The proposed treatment algorithm provides a pathway of the clinical steps needed to allow individualized surgical planning, rehabilitation focus, and, finally, optimal prosthetic control.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author Contributions

Conception and design: Aszmann, Hruby, Salminger. Acquisition of data: Hruby, Sturma, Mayer. Analysis and interpretation of data: Hruby, Sturma, Mayer. Drafting the article: Hruby, Sturma, Mayer, Pittermann, Salminger. Critically revising the article: Aszmann, Salminger. Statistical analysis: Hruby, Sturma, Salminger. Study supervision: Aszmann.

Supplemental Information

Videos

Video 1. <https://vimeo.com/182861187>.

Previous Presentations

Portions of this work were presented in oral form at the Annual Conference of the American Society of Reconstructive Microsurgery, held in Nassau, the Bahamas, in January 2015.

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