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Targeted muscle reinnervation to improve electromyography signals for advanced myoelectric prosthetic limbs: a series of seven patients

Harley Myers, David Lu, Steven J. Gray and Frank Bruscino-Raiola
Department of Plastic, Hand and Faciomaxillary Surgery, Alfred Health, Melbourne, Victoria, Australia

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myoelectric, osseointegration, prosthetic, targeted muscle reinnervation.

Correspondence
Dr Harley Myers, Department of Plastic, Hand and Faciomaxillary Surgery, The Alfred, 55 Commercial Road, Melbourne, VIC 3004, Australia.
Email: harleymyers@gmail.com

H. Myers MBBS, MS; **D. Lu** MBBS; **S. J. Gray**; **F. Bruscino-Raiola** MBBS.

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Abstract

Background: Upper limb amputation is a devastating injury. Patients may choose to use a passive prosthesis, a traditional body-powered prosthesis or a myoelectric prosthesis driven by electromyography (EMG) signals generated by underlying muscles. Targeted muscle reinnervation (TMR) aims to surgically create strong and reliable signals to permit the intuitive use of a myoelectric prosthesis with the greatest number of movements possible. We review the Alfred Hospital experience of using TMR to improve upper limb prosthesis control.
Methods: A retrospective review of all cases of TMR performed at the Alfred Hospital was undertaken. Patient demographics, injury, surgical complications and outcomes were examined. Comparison was made to preoperative prosthesis use.
Results: Seven patients have undergone TMR to improve upper limb prosthesis control at the Alfred Hospital between 2015 and 2018. Within the patient group, pre-TMR EMG signal numbers ranged from 1 to 2, and post-TMR signal numbers ranged from 3 to 5. Six patients were able to achieve six degrees of freedom post-operatively, and one patient achieved four degrees. No patients required the use of co-contraction to switch function post-operatively. There were no significant surgical complications.
Conclusion: The use of TMR to improve and increase the number of EMG signals has been successful in generating more degrees of freedom for upper limb amputees with myoelectric prostheses.

Introduction

Targeted muscle reinnervation (TMR) is a recent surgical technique designed to improve myoelectric prosthetic control for upper limb amputees. The procedure was first performed in 2002 at the Northwestern Memorial Hospital (Chicago, IL, USA), and reported in the literature in 2004.[1] Initially designed to provide greater motor control of a myoelectric prosthesis for a patient with bilateral amputations at shoulder disarticulation level, the promising results from TMR have seen the expansion of application to transhumeral and transfemoral amputees.[2,3]

The surgical goal of TMR is to create new and reliable electromyography (EMG) signals in amputees to provide greater control over myoelectric prostheses. Residual upper limb nerves in the stump are paired with muscles that retain contractility but no longer have a biomechanical function. Following successful neurotization, these muscles biologically amplify nerve signals and serve as a conduit to the skin surface, thus providing new, discrete EMG signals available for prosthetic control. The rerouting of nerve signals also offers a more intuitive control interface by using specific nerve branches to control analogous joints on the myoelectric prosthesis.[1,4,5] For example, radial nerve, which anatomically supplies elbow, wrist and hand extensors but has lost its native targets, can be used to create EMG signals to control prosthetic 'elbow extension' and 'hand open' independently. Reported restoration of basic upper limb sensory function through targeted sensory reinnervation (TSR) via prosthetic limbs[2,6,7] also brings about the exciting possibility of finally achieving bidirectional prosthesis control.

Existing literature reports TMR being performed at only a limited number of key centres around the world. The Alfred TMR/Osseointegration Program began implementation in 2014, with its first patient undergoing TMR in Chicago in 2015, and subsequently in Australia in 2016. As of November 2017, seven patients have undergone primary TMR and one patient has undergone revision TMR. The aim of this study is to review the results of the Alfred TMR Program to date and identify the patient and surgical factors that contribute to improved outcomes.

Methods

A retrospective review was conducted of patient data collected by the Alfred Hospital (Melbourne, Victoria, Australia) TMR/Osseointegration Program from 1 October 2016 to 30 November 2017. All patients who underwent TMR with the Alfred Hospital programme during the study period were included.

Data collected included patient demographics; presenting physical defect and mechanism of injury; preoperative prosthesis type and control system; number of preoperative EMG signals; operative details and post-operative complications; post-operative prosthesis type and control system; and number of post-operative EMG signals.

In accordance with the Alfred Health institutional ethics policies, ethical review was not required to undertake this research. All participants provided written consent for their information to be used in this study.

Surgical methods

Each surgical approach is tailored to the individual case, taking into account the soft tissue envelope, available nerves and muscles, preoperative signal sites and their reliability, and patient and surgeon joint agreement on functional goals.

Our generalized surgical approach is as follows: we begin exploring the posterior compartment of the arm in a prone position, and specifically explore the potential to create two signals from the radial nerve – an isolated distal radial nerve signal and an isolated proximal radial nerve signal. The usual muscle targets used are long and lateral heads of triceps. We then turn prone to explore the anterior compartment and assess the capacity to isolate muscle targets for the remaining nerves. Usual options are coracobrachialis, long head of biceps, short head of biceps and brachialis. If insufficient muscle targets are available, we utilize a pedicled serratus muscle flap to import muscle targets into the residual limb.

Table 1 outlines the preoperative nerve–muscle pairings, and actions with those pairings preoperatively, and contrasts this with the post-TMR nerve–muscle pairings and functions achieved post-operatively in our series.

Post-operative management: prosthetic fitting and training method

Significant challenges exist in realizing the surgical potential of TMR and its application in prosthetic control. Effective management and optimal outcome requires a collaborative approach between the surgical and rehabilitation teams, with a shared understanding of the relationship between the TMR surgical approach, prosthetic control strategy and realistic functional potential of the patient. Our rehabilitation team includes prosthetists, occupational therapists, physiotherapists and rehabilitation specialists.

The rehabilitation process, including the post-operative timing of EMG site testing and key early training strategies used, the timing of initial diagnostic prosthetic fitting (trial componentry), evaluation and training, and the timing of definitive prosthetic prescription and long-term training, is depicted in timeline format in Figure S1. Active rehabilitation commences 6 weeks post-TMR surgery with definitive prosthetic prescription typically occurring within 12 months. The duration of the rehabilitation process is dependent on individual factors such as level of amputation, chronicity of injury, timeframes for reinnervation and strengthening, prosthetic experience and previous control strategies, engagement and compliance with therapy and prosthetic goals.

Results

Demographics are presented in Table 2. Seven patients have been treated by the Alfred TMR Program to improve upper limb prosthesis control between 1 October 2016 and 30 November 2017. Age range was 37–61 years, with a predominance of males suffering from transection/crush and avulsion injuries. Time from injury to operation ranged from 9 to 253 months.

Within the patient group, pre-TMR EMG signal numbers ranged from 1 to 2, and post-TMR signal numbers ranged from 3 to 5 (Table S1). Nerve–muscle pairings varied throughout the patient group, and comparisons between preoperative pairings and actions, and post-operative pairings and actions are presented in Table 2. All except one patient achieved at least doubling of their preexisting EMG signals (Fig. 1).

Six patients were able to achieve six degrees of freedom post-operatively, and one patient achieved four degrees. No patients required the use of co-contraction to switch between myoelectric function/joint post-operatively. There were no significant surgical complications, as seen in Table S2, which also shows post-operative prosthesis used by each patient.

Discussion

The advent of myoelectric prostheses has provided upper limb amputees with a new generation of artificial limbs that are controlled with myogenic EMG signals. While this development theoretically results in greater control of the prosthesis, the functional outcome is usually limited by the number of reliable transcutaneous EMG signals that are available to control the programmed prosthesis. Multiple studies have now demonstrated that TMR is a successful procedure that creates reliable EMG signals that translate into enhanced control of myoelectric prostheses, and this study adds to that body of evidence.

In this series, all patients were observed to have an increase in number of detectable EMG signals (range of 1–3 increased signals, average of 2.3). Eighty-six percent of patients (6/7) doubled the number of detectable and reliable signals that could be used to control a myoelectric prosthetic arm. The increased number of signals corresponded to a greater degree of prosthetic control, with 71% (5/7) of patients achieving additional degrees of freedom (range of 2–6 increased movements) post-operatively as compared to preoperatively. The remaining 29% (2/7) had an unchanged six degrees of freedom pre- and post-operatively, but through TMR were able to obviate the need for muscle co-contraction and achieve more fluid control of their prosthetic.

One patient in this series did not achieve six degrees of prosthetic freedom post-operatively. However, this was also the only below-elbow amputee. This patient gained three additional signals post-

Table 1 Nerve–muscle pairings and actions (preoperative versus post-operative)

	Pre-operative			Post-operative		
1	**2 signal sites – 4 movements, co-contraction switching between pairs**			**4 TMR signal sites – 6 movements with COAPT/Pattern Recognition**		
	Musc.cut	-> Biceps	-> Hand close	Musc.cut	-> Biceps (half)	-> Elbow flexion
	Radial	-> Triceps	-> Hand open	Prox. radial	-> Triceps long head	-> Elbow extension
	Musc.cut	-> Biceps	-> Supination (after co-contract switching)	Median	-> Biceps (half)	-> Hand close
	Radial	-> Triceps	-> Pronation (after co-contract switching)	Dist. radial	-> Triceps lat. head	-> Hand open
						-> Supination (pattern recognition)
						-> Pronation (pattern recognition)
2	**2 signal sites – 6 movements, co-contraction switching between pairs**			**3 TMR signal sites – 6 movements with COAPT/Pattern Recognition**		
	Musc.cut	-> Biceps	-> Elbow flexion	Musc.cut	-> Biceps short head	-> Elbow flexion
	Radial	-> Triceps	-> Elbow extension	Prox. radial	-> Triceps long head	-> Elbow extension
	Musc.cut	-> Biceps	-> Hand close (after co-contract switching)			-> Hand close (pattern recognition)
	Radial	-> Triceps	-> Hand open (after co-contract switching)	Distal radial	-> Triceps lat. head	-> Hand open
	Musc.cut	-> Biceps	-> Supination (after co-contract switching)			-> Supination (pattern recognition)
	Radial	-> Triceps	-> Pronation (after co-contract switching)			-> Pronation (pattern recognition)
3	**2 signal sites – 4 movements, co-contraction switching between pairs**			**5 TMR signal sites**		
	Musc.cut	-> Biceps	-> Elbow flexion	Musc.cut	-> Coracobrachialis	-> Elbow flexion
	Radial	-> Triceps	-> Elbow extension	Prox.radial	-> Triceps long head	-> Elbow extension
	Musc.cut	-> Biceps	-> Hand close (after co-contract switching)	Median	-> Serratus slip	-> Hand close
	Radial	-> Triceps	-> Hand open (after co-contract switching)	Dist.radial	-> Triceps lat. head	-> Hand open
				Ulnar	-> Serratus slip	-> Supination
						-> Pronation (pattern recognition)
4	**2 signal sites – 6 movements, co-contraction switching between pairs**			**4 TMR signal sites – 6 movements with COAPT/Pattern Recognition**		
	Musc.cut	-> Biceps	-> Elbow flexion	Musc.cut	-> Biceps long head	-> Elbow flexion
	Radial	-> Triceps	-> Elbow extension	Prox.radial	-> Triceps long head	-> Elbow extension
	Musc.cut	-> Biceps	-> Hand close (after co-contract switching)	Ulnar	-> Biceps short head	-> Hand close
	Radial	-> Triceps	-> Hand open (after co-contract switching)	Dist.radial	-> Triceps lat. head	-> Hand open
	Musc.cut	-> Biceps	-> Supination (after co-contract switching)			-> Supination (pattern recognition)
	Radial	-> Triceps	-> Pronation (after co-contract switching)			-> Pronation (pattern recognition)
5	**1 signal site – 2 movements**			**4 TMR signal sites – 4 movements with COAPT/Pattern Recognition**		
			Native elbow flexion			Native elbow flexion
			Native elbow ext.			Native elbow extension
	Dist. radial	-> ECRL	-> Hand open	Dist.radial	-> ECRL	-> Hand open
			-> Hand close (default position)	Median	-> FCR	-> Hand close
				Prox.radial	-> Brachioradialis	-> Supination
				Median	-> Pronator teres	-> Pronation
6	**2 signal sites (inadequate amplitude signals; using passive limb only)**			**4 TMR signal sites – 6 movements with COAPT/Pattern Recognition**		
	Musc.cut	-> Biceps	-> ~~Elbow flexion~~	Musc.cut	-> Biceps	-> ~~Elbow flexion~~ (inadequate signal)
	Radial	-> Triceps	-> ~~Elbow extension~~	Prox.radial	-> Triceps	-> Elbow lock/unlock*
			-> ~~Hand close (after co-contract switching)~~	Median	-> Serratus slip	-> Hand close
			-> ~~Hand open (after co-contract switching)~~	Dist.radial	-> Serratus slip	-> Hand open
				Ulnar	-> Serratus slip	-> Supination
						-> Pronation (pattern recognition)
				*(manual positioning by contralat. limb)		
7	**2 signal sites – 4 movements, co-contraction switching between pairs**			**5 TMR signal sites – 6 movements with COAPT/Pattern Recognition**		
	Musc.cut	-> Biceps	-> Elbow flexion	Musc.cut	-> Coracobrachialis	-> Elbow flexion
	Radial	-> Triceps	-> Elbow extension	Radial	-> Triceps long head	-> Elbow extension
	Musc.cut	-> Biceps	-> Hand close (after co-contract switching)	Median	-> Serratus slip	-> Hand close
	Radial	-> Triceps	-> Hand open (after co-contract switching)	Dist.radial	-> Serratus slip	-> Hand open
				Ulnar	-> Serratus slip	-> Supination (pattern recognition)
						-> Pronation (pattern recognition)

†Manual positioning by contralateral limb. ECRL, extensor carpi radialis longus; FCR, flexor carpi radialis longus; lat., lateral; Prox., proximal; TMR, targeted muscle reinnervation.

Table 2 Demographics

Patient	Gender	Age	Injury	Mechanism of injury	Date of injury	Date of TMR	Injury to TMR (months)
1	Male	44	Bilateral transhumeral	Sepsis	June 2012	October 2015 Revision September 2016	40 51
2	Male	54	Right transhumeral	Avulsion	September 1999	August 2016	203
3	Male	54	Right transhumeral	Crush	May 2007	October 2016	68
4	Male	61	Right transhumeral	Degloving/crush	October 1995	November 2016	253
5	Male	49	Right transradial	Transection/crush	October 2005	December 2016	134
6	Female	37	Left transhumeral	Avulsion	April 2016	January 2017	9
7	Male	61	Right transhumeral	Transection/crush	December 2003	March 2017	159

TMR, targeted muscle reinnervation.

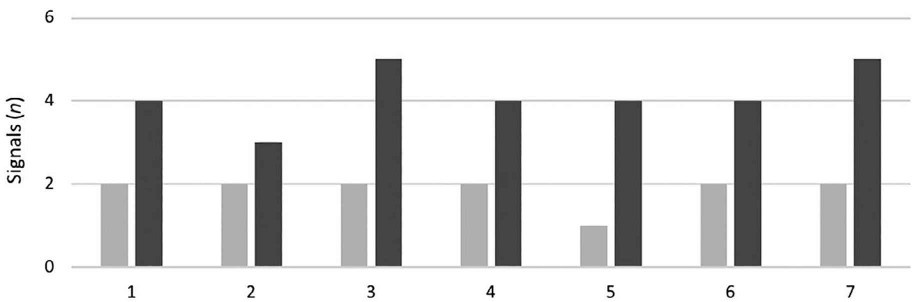

Fig. 1. Preoperative versus post-operative electromyography signals (number). ■, Pre-targeted muscle reinnervation (TMR); ■, post-TMR.

TMR and now controls a transradial myoelectric prosthesis with four degrees of prosthetic freedom. The below-elbow nature of the amputation means that the combination of native elbow and prosthetic arm movements results in a total of six degrees of freedom. With this consideration, all patients in this series achieved six degrees of freedom post-TMR.

The significance of augmenting signal quality cannot be understated. This is a separate but synergistic benefit to the increase in number of EMG signals that TMR is able to deliver. The success of TMR hinges on manipulation of the soft tissue envelope during the procedure to ensure that surface signals are of adequate amplitude and purity. This is achieved through the careful placement of reinnervated muscle targets and use of autologous pedicled adipofascial flaps to (i) debulk overlying subcutaneous tissue and (ii) insulate each signal to minimize cross-talk or signal contamination between EMG signal detection points. In our series, the value of signal quality is particularly evident in patients 1 and 2. Patient 1 initially underwent TMR overseas but could not reliably achieve sufficient signal amplitude due to poorly conducting overlying subcutaneous tissues. Revision surgery performed at the Alfred thinned overlying skin and subcutaneous tissue, and adipofascial flaps were re-fashioned and interposed between muscle targets to minimize cross-talk between signals. Clear signals were achieved after this revision surgery. Similarly, patient 2 had two detectable signals pre-TMR; however, inconsistent pickup of either signal rendered the myoelectric prosthesis ineffective and unreliable. Both of these signal sites were simultaneously revised when the patient underwent TMR, resulting in three signals post-operatively of much higher quality. In this case, the effective increase in signals is from zero to three usable signals.

Intuitive control of a prosthetic limb achieved through the pairing of signals with myoprosthesis actions that are analogous to native neuromuscular pairings is key to the quality of life improvement that underlies the above-mentioned results. With the creation of EMG signals derived from nerves that were previously non-contributory to the amputee, the ability to deliver a prosthetic limb that responds reliably and intuitively becomes possible. This then enables an expedited rate of adoption with a decreased training period, an overall improved uptake and enduring utilization of the myoprosthetic limb. While this is not represented in pure quantitative or qualitative data in this series, it is our clear observation, and one of the key benefits to this endeavour.

Our experience strongly suggests that a sustained multidisciplinary approach to patient selection, workup and rehabilitation is crucial in achieving satisfactory functional outcomes. The Alfred TMR Program consists of plastic surgeons working closely with physicians, prosthetists, occupational therapists, physiotherapists and psychologists. Preoperatively, patients are assessed and deemed to have adequate insight and motivation to adhere to the intensive rehabilitation prior to proceeding. In the post-operative period, patients need to comply with complex and often repetitive training regimes designed by the prosthetists and other allied health professionals.

Once satisfactory prosthetic control systems have been established, there is an ongoing requirement for hardware maintenance and stump management. The importance of this is illustrated in the case of patient 1, who initially underwent TMR overseas and went on to receive revision surgery at the Alfred Hospital. After returning to Australia, this patient experienced unreliable EMG signal pickup and abandoned the use of his myoelectric prosthesis. He was unable to solve the issue with the original surgeon or prosthetist due to geography. Only after receiving revision TMR 11 months after his original surgery was he able to begin using his myoelectric prosthesis again. In this case, an 11-month set-back may have been avoided if he had remained in close geographical proximity and received ongoing support from with his original treating team. Since receiving revision surgery and regaining prosthesis control, this patient moved interstate, and once again geography prevented the ongoing management of his prosthesis. Unfortunately, new prosthetic pick-up positioning issues are now once again preventing him from using his myoelectric limbs, despite having strong and reliable signals. This case poignantly demonstrates the critical role multidisciplinary support plays in ensuring the ongoing success and longevity of the human–machine interface, and the gain in quality of life associated with the TMR procedure.

Future directions

Immediate/acute TMR

Presently, the majority of Alfred TMR candidates have been long-term amputees (injury–surgery range of 9–253 months, average of 132 months). We believe that chronicity of injury has multiple implications on the success of rehabilitation following TMR.

(1) Following amputation, residual muscles of the stump rapidly fall into disuse and undergo significant atrophy – independent of whether they remain natively innervated. We hypothesize that this may contribute to poorer potential signal quality, and translates to longer rehabilitation and training time post-TMR to generate detectable EMG signals.

(2) At a more proximal level, afferent axotomy from the original insult may cause partial or total denervation of local muscles, leading to progressive loss of receptivity of the neuromuscular junctions (NMJs).[8] The irreversible nature of this NMJ injury suggests that (delayed) reinnervation through TMR will be less effective in generating reliable signals with increased chronicity. This may also contribute to overall poorer potential signal quality.

(3) Long-term amputees who have been trained to use conventional prostheses develop anomalous patterns of EMG signals, as traditional prosthetic control systems are often counterintuitive and demand significant alterations to the combination of native muscle groups activated for each movement. As such, following TMR, significant periods of pattern 'un-learning' are necessary before true (intuitive) prosthesis re-training can commence. For example, a typical two-site control myoelectric prosthesis requires a transhumeral amputee to generate signals from biceps and triceps to activate antagonistic movements of the prosthetic elbow, wrist and hand. Post-TMR, the patient will need to 'un-learn' the aberrant activation of musculocutaneous and radial nerves in the control of wrist and hand flexion, and rather learn to control hand and wrist movements with median, ulnar and distal radial nerves.

(4) Postamputation neuromas form a significant barrier to the adoption of both conventional and myoelectric prostheses. Chronic pain associated with neuromas often prevent consistent fitting of prosthetic arms, and simultaneously results in significant psychological and physical suffering through the activation of pathological pain pathways. TMR has been shown to improve postamputation neuroma pain[9] by theoretically providing injured nerve endings with a distal target for reinnervation. Earlier and improved pain control would serve to reduce the complex neurophysiological response and prevent establishment of chronic pain pathways.

In light of the above, early TMR performed in the acute post-injury stage and prior to fitting of a prosthesis theoretically allows for greater preservation of muscle mass, maintenance of NMJ receptivity, improved pain control and a more intuitive and expedited training process.

Osseointegration/TMR

With the current TMR technique and prosthesis design, obstacles still exist in ensuring immediate and accurate pickup of surface EMG signals. Pliability of the soft tissue, change in body habitus and perspiration are examples of factors that can disrupt the human–prosthesis interface.

The advent of osseointegration in the 1950s by Li and Brånemark has provided an anchoring system that circumvents many of the difficulties associated with a traditional socket prosthesis. Its advantages include physiological osseous weight bearing, osseoperceptive feedback and reduced strain on soft tissues.[10] Lifestyle factors such as ease of application and removal of prosthesis, and rapid exchange of customized activity-specific prostheses are also factors not to be underappreciated.

All patients in this series who have undergone TMR at the Alfred have also had osseointegration procedures with externally protruding abutments. Myoelectric limbs can be relatively quickly mounted to these abutments, freeing the patient from the need to use harnesses, and improving usability, exchangeability and reliability of prostheses. Figure 2 depicts one of the patients managed via the Alfred Hospital Advanced Surgical Amputee Programme (Osseointegration, TMR and Soft Tissue Reconstruction programme), and demonstrates

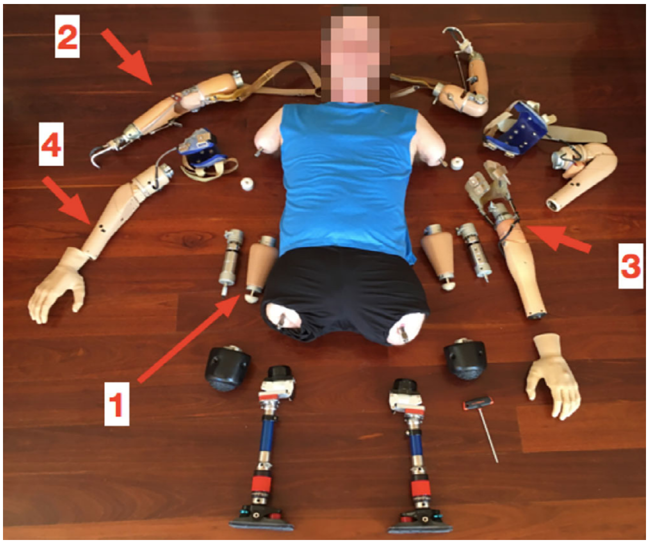

Fig. 2. Quadrilateral amputee with multiple prostheses. 1, Sleeping prosthesis; osseointegration connector with a structural rod, foam cover and a hemispherical end piece (custom 3D printed). 2, Body powered prosthesis; bilateral harness controlling a manual locking elbow, bilateral five function wrist unit and bilateral hooks. 3, Conventional myoelectric prosthesis; two electrodes over biceps and triceps controlling motorised wrist and hand. Manual locking elbow. 4, Pattern recognition prosthesis with COAPT pattern recognition, controlling a Utah 3+ motorised elbow and wrist unit. BeBionic hand.

the number of different prostheses – each tailored for a different purpose or activity – that can be mounted and exchanged quickly using modern osseointegrated abutments.

Osseointegrated anchoring systems designed by Osseointegrated Prostheses for the Rehabilitation of Amputees feature a central channel that can allow for passage of electrodes from stump to prosthesis. There has been one successful case of an osseointegrated human–machine gateway[10] reported in the literature, where electrodes were implanted into the distal stump muscles of a transhumeral amputee, and signals were conducted to the prosthesis through the osseointegrated fixture and abutment. Passing the TMR-derived EMG signals to the prosthesis through the abutment eliminates many of the potential issues associated with external EMG pick-up sites. This may become a more frequently used system in the future, and one that would represent a significant step forward in refining amputee prosthetic limb control.

Conclusion

The Alfred Hospital has successfully implemented a TMR programme delivered by a multidisciplinary team, and is the only centre in Australia to do so to date. This series demonstrates that the use of TMR to improve and increase the number of EMG signals has been successful in generating more degrees of freedom for upper limb amputees with myoelectric prostheses. Ongoing support provided through the multidisciplinary approach to rehabilitation is essential to the success of TMR, and the Alfred Hospital TMR Program benefits synergistically from its ability to also deliver osseointegration to patients.

Conflicts of interest

SJG is a Director of Surgien Pty Ltd, which is the Australian sponsor with the Federal Department of Health Australia for O.P.R.A. (Integrum AB Sweden), the manufacturing company for osseointegrated implants used by patients in this study. No other author has any financial support or relationships that may pose conflicts of interest.

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Supporting information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Figure S1. Rehabilitation timeline.

Table S1. Preoperative versus post-operative electromyography signals.

Table S2. Complications and long-term prosthesis used post targeted muscle reinnervation.