Hand Surgery and Rehabilitation 44 (2025) 101782

Available online at
ScienceDirect
www.sciencedirect.com

Elsevier Masson France
EM|consulte
www.em-consulte.com

Original article

Targeted muscle reinnervation in the upper arm: A functional anatomical study

Feng Li [a], Yong Yang [a,*], Bin Li [a], Mengqi Cao [a], Qipei Wei [a], Weiguang Zhang [b]

[a] *Department of Hand Surgery, Beijing Jishuitan Hospital, Beijing 100035, China*
[b] *Department of Human Anatomy, Histology and Embryology, Peking University School of Basic Medical Sciences, Beijing 100191, China*

A R T I C L E I N F O

Article history:
Received 18 June 2024
Received in revised form 9 September 2024
Accepted 11 September 2024
Available online 25 September 2024

Keywords:
Anatomy
Targeted muscle reinnervation
Ulnar nerve
Median nerve
Radial nerve

A B S T R A C T

Background: The aim of this study was to accurately locate the neural fascicle controlling hand movement in the upper arm, to enhance expression of motor intention after targeted muscle reinnervation.
Methods: The right sides of the median, ulnar and radial nerves were dissected from distal to proximal in 6 fresh cadaver specimens. The sectional location and diameter of the functional fascicle were measured at 10 and 20 cm below the acromion. The diameter of the main muscle branches of muscle reinnervation target muscles was measured.
Results: The median nerve branch of finger and wrist flexion was mainly located between the 9 and 12 o'clock positions in the plane 10 and 20 cm below the acromion, where the diameter of the nerve fascicle was 2.07 and 2.04 mm, respectively. The ulnar nerve branch of finger and wrist flexion was mainly located between the 8 and 12 o'clock positions, with a diameter of respectively 1.80 and 1.99 mm. The radial branch of finger and wrist extension was mainly located between the 10 and 2 o'clock positions in the plane 10 cm below the acromion and between 6 and 12 o'clock in the plane 20 cm below the acromion, with a diameter of respectively 2.57 and 3.03 mm.
Conclusions: The nerve fascicles innervating the flexor and extensor fingers were distributed in relatively constant regions of the median, ulnar and radial nerve trunks, and their diameters closely matched the muscle branches of the target muscle.

Background

Upper-limb amputation is a devastating injury that results in loss of form and function. Prosthetic options are limited. Current prostheses may restore basic motor functions for crucial activities, but are cumbersome to operate and are often abandoned. Targeted muscle reinnervation (TMR) surgery can improve function to a greater degree than traditional prostheses, allowing easier intuitive function of myoelectric prostheses.

Innervation strategies vary [1–3]. The relatively standardized surgical protocol for transhumeral TMR is as follows. The median nerve is transferred to the short head of the biceps brachii motor branch to provide a signal for hand closing or pronation; the ulnar nerve is transferred to a residual brachialis motor branch to provide an additional signal for hand closing; and the radial nerve is transferred to the lateral head of the triceps motor branch to provide a signal for hand opening or supination. The native innervation to the long head of the biceps and the long head of the triceps muscles is preserved to allow elbow flexion and extension.

Although all available strategies involve median, ulnar and radial nerve transfers, these are mixed nerves, with motor nerve fibers that innervate the muscle groups of different functions, and their diameter is larger than the muscle branches of the target muscle. Planitzer et al. reported the distribution of the motor branches of the median nerve in the distal forearm and hand for functional electrical stimulation [4]. In upper-limb amputation, if the neural fascicle controlling hand movement can be accurately located in the upper arm, a patient who has undergone TMR surgery may easily and accurately perform hand opening and closing using a prosthesis. Based on this assumption, we designed and performed the functional anatomical study described below.

Methods

Six fresh cadaver specimens were obtained through the Anatomy Laboratory of the Health Science Center of Peking University. The right median, ulnar and radial nerves were

* Corresponding author.
E-mail address: 0414yang@sina.com (Y. Yang).

https://doi.org/10.1016/j.hansur.2024.101782
2468-1229/

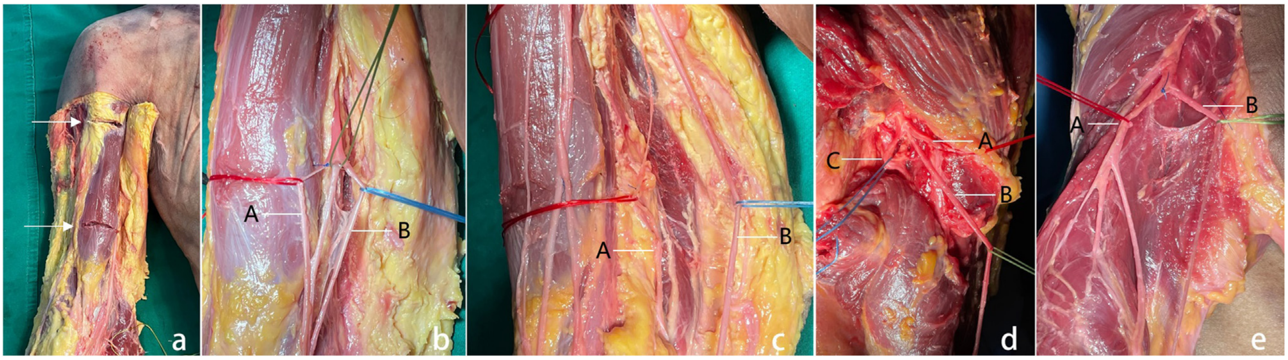

Fig. 1. (a) The plane 10 and 20 cm below the acromion was marked. **(b)** At 20 cm below the acromion, the median nerve was divided into three parts: (A) finger and wrist flexion branch, (B) anterior interosseous nerve, and terminal branch. **(c)** At 20 cm below the acromion, the ulnar nerve was divided into two parts: (A) finger and wrist flexion branch and (B) terminal branch. **(d)** At 10 cm below the acromion, the radial nerve was divided into three parts: (A) finger and wrist extension branch, (B) superficial branch, and (C) elbow extension branch. **(e)** At 20 cm below the acromion, the radial nerve was divided into two parts: (A) finger and wrist extension branch and (B) superficial branch.

dissected under 4× loupe magnification retrogradely from distal to proximal, starting with the forearm and progressing to the upper arm. The distribution and diameter of functional fascicles were measured at 10 and at 20 cm below the acromion (Fig. 1).

The cadaver was placed in supine position with the arm in 90° abduction, simulating the surgical position. All branches of the median nerve in the forearm were dissected, and divided into three parts: finger and wrist flexion branch for pronator teres, palmaris longus, flexor carpi radialis and flexor digitorum superficialis, anterior interosseous nerve, and terminal branch. Median nerve trunk at 10 and 20 cm below the acromion was then dissected and 12-o'clock position marked with 9-0 Prolene, preventing a change of location of the functional nerve fascicles after they were completely freed. The distribution of each part in the main nerve was described, and the diameter of each part was measured. The ulnar nerve was dissected similarly and divided into two parts: the finger and wrist flexion branch for flexor carpi ulnaris and flexor digitorum profundus and the terminal branch.

The cadaver was placed in lateral position with the arm in 0° adduction while dissecting the radial nerve, and the 12-o'clock position was marked at 10 and 20 cm below the acromion. At 20 cm below the acromion, the radial nerve was divided into two parts: the superficial branch and the finger and wrist extension branch (deep branch). At 10 cm below the acromion, the radial nerve was divided into three parts, the additional part being the elbow extension branch. The distribution of each part in the main nerve was described, and the diameter of each part was measured.

After dissection of the median, ulnar and radial nerves, the target muscle branches were dissected and their diameters were measured: long head branch of the biceps brachii, short head branch of the biceps brachii, long head branch of the triceps brachii, lateral head branch of the triceps brachii, lateral pectoral nerve, medial pectoral nerve, latissimus dorsi muscle branch, and deltoid muscle branch (Fig. 2).

Results

The median nerve finger and wrist flexion branch was mainly located between the 9 and the 12 o'clock positions in the planes 10 and 20 cm below the acromion (i.e., radial volar quadrant), with diameters of 2.07 and 2.04 mm, respectively. The ulnar nerve finger and wrist flexion branch was mainly located between the 8 and 12 o'clock positions, also in the radial volar quadrant, with diameters of 1.80 and 1.99 mm, respectively. The radial finger and wrist extension branch was mainly located between the 10 and 2 o'clock positions in the plane 10 cm below the acromion and between the 6 and 12 o'clock positions in the plane 20 cm below the acromion, with diameters of 2.57 and 3.03 mm, respectively (Table 1, Figs. 3–5).

The TMR target muscle branches (long head branch of the biceps brachii, short head branch of the biceps brachii, long head branch of the triceps brachii, lateral head branch of the triceps brachii, lateral pectoral nerve, medial pectoral nerve, latissimus dorsi muscle branch, and deltoid muscle branch) had diameters similar to those of the donor nerve, which was more conducive to anastomosis (Fig. 6).

Discussion

Targeted muscle reinnervation was first described for improvement of function after upper-extremity amputation, and has been an exciting advance in the field of prosthetics, allowing easier

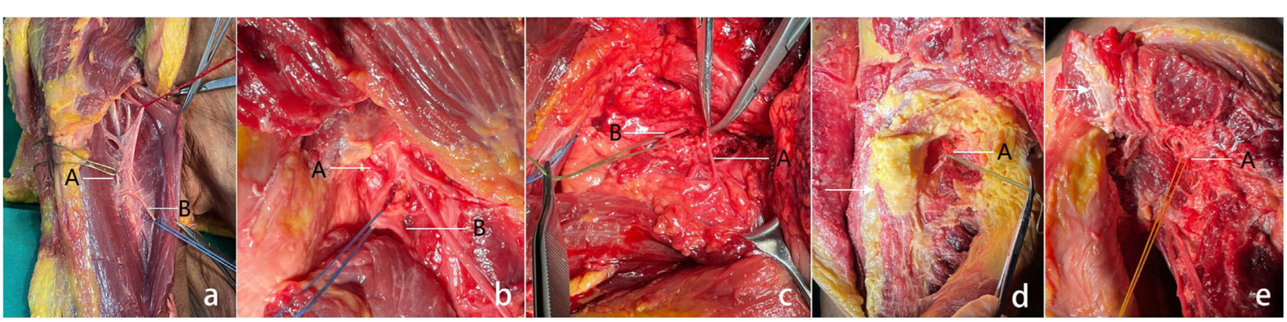

Fig. 2. (a) The branches of the biceps brachii: (A) long head branch of the biceps brachii, and (B) short head branch of the biceps brachii. **(b)** The branches of the triceps brachii: (A) long head branch of the triceps brachii, and (B) lateral head branch of the triceps brachii. **(c)** The branches of the pectoralis major: (A) lateral pectoral nerve, and (B) medial pectoral nerve. **(d)** The latissimus dorsi muscle branch. The arrow indicates the anterior margin of the latissimus dorsi muscle. (A) Thoracodorsal nerve. **(e)** (A) The deltoid muscle branch. The arrow indicates the raised deltoid muscle.

Table 1
Diameter of each part of the median, ulnar and radial nerves.

	Median nerve			Ulnar nerve		Radial nerve		
	Finger and wrist flexor	Terminal branch	Anterior interosseous nerve	Finger and wrist flexor	Terminal branch	Finger and wrist extensor	Superficial branch	Elbow extension branch
10 cm below acromion	2.07 ± 0.21	2.17 ± 0.13	1.85 ± 0.13	1.80 ± 0.15	2.27 ± 0.23	2.57 ± 0.20	2.31 ± 0.22	2.81 ± 0.29
20 cm below acromion	2.04 ± 0.15	1.87 ± 0.15	2.02 ± 0.12	1.99 ± 0.21	2.67 ± 0.30	3.03 ± 0.13	2.71 ± 0.10	none

Data are presented as mean ± standard deviation.
Measurements in millimeters.

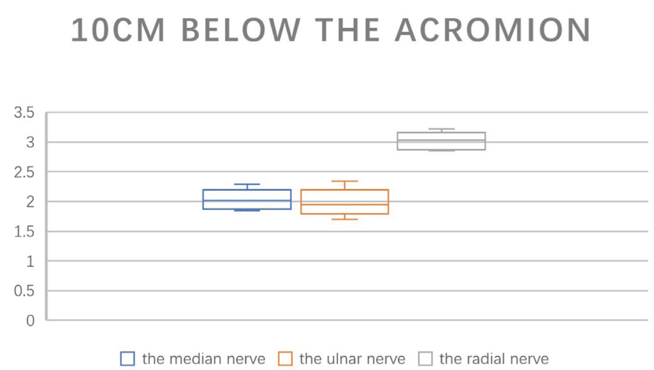

Fig. 3. The diameter of the median nerve finger and wrist flexion branch, ulnar nerve finger and wrist flexion branch, and radial nerve finger and wrist extension branch in the plane 10 cm below the acromion.

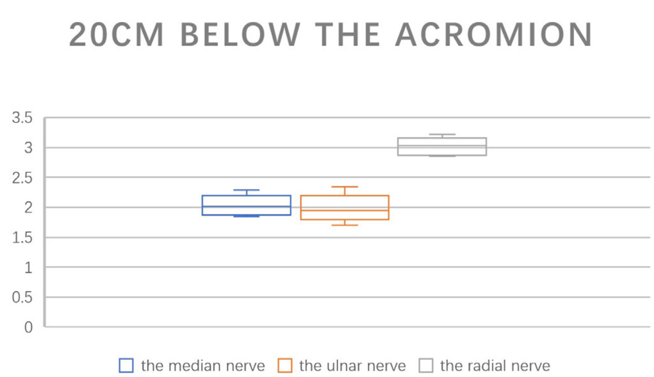

Fig. 4. The diameter of the median nerve finger and wrist flexion branch, ulnar nerve finger and wrist flexion branch, and radial nerve finger and wrist extension branch in the plane 20 cm below the acromion.

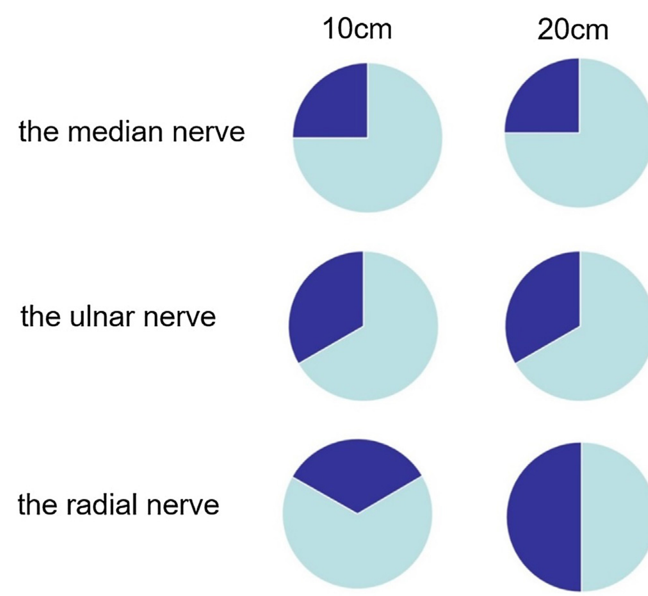

Fig. 5. The median nerve finger and wrist flexion branch (dark blue region) was mainly located between the 9 and 12 o'clock positions in the planes 10 and 20 cm below the acromion. The ulnar nerve finger and wrist flexion branch (dark blue region) was mainly located between the 8 and 12 o'clock positions in the planes 10 and 20 cm below the acromion. The radial finger and wrist extension branch (dark blue regions) was mainly located between the 10 and 2 o'clock positions in the plane 10 cm below the acromion and between the 6 and 12 o'clock positions in the plane 20 cm below the acromion.

intuitive function of myoelectric protheses [4,5]. Since its initial development, TMR surgery has become widespread and has improved prosthetic function and revolutionized neuroma treatment [2,6–13]. Although it is a worthwhile procedure, it has some limitations in terms of prosthetic control [8]. Compared with transradial TMR surgery, transhumeral TMR surgery is more challenging and provides poorer myoelectric prothesis control [14]. Patients with transhumeral amputation have fewer residual muscles for detectable electromyographic (EMG) signals and nerve transfer procedures, and must use their residual upper limb, shoulder girdle, neck and head to operate the prosthesis.

In the upper-arm, the median, ulnar and radial nerves are mixed nerves with a larger diameter than that of the targeted muscle branch that is transferred. In theory, the targeted muscle will attain good muscle strength after nerve transfer because the donor nerve has more corresponding motor nerve fibers. If the neural fascicle that controls hand movement can be accurately located in the upper arm, a patient who has undergone TMR surgery can easily and accurately produce the intended movement of the prosthesis. Therefore, determining the location of the functional nerve fascicles of the median and ulnar nerves controlling finger and wrist flexion and the location of the functional nerve fascicle of the radial nerve controlling finger and wrist extension improves the expression of the patient's intention to control the movement of the hand after TMR.

All previous reports on the anatomy related to TMR surgery focused on the distance to the branch muscle relative to proximally based bony landmarks [15,16]. In the present study, the relative positions of the muscle branches in the cross-section were determined, and we found that the fascicle of the donor nerve we intended to anastomose was distributed in a particular quadrant. Salminger et al. [17] reported that, particularly in patients with additional nerve damage requiring repair, nerve transfer must be adapted so as to minimize non-synergistic matching between the cortical organization and target muscle function. Therefore, only cognitively "simple" nerve transfers should be performed. Transfers of both median and ulnar nerves may be difficult to incorporate into prosthetic function, because even amputees without nerve damage have difficulty in cognitively separating these two signals [18]. In the present study, the ulnar

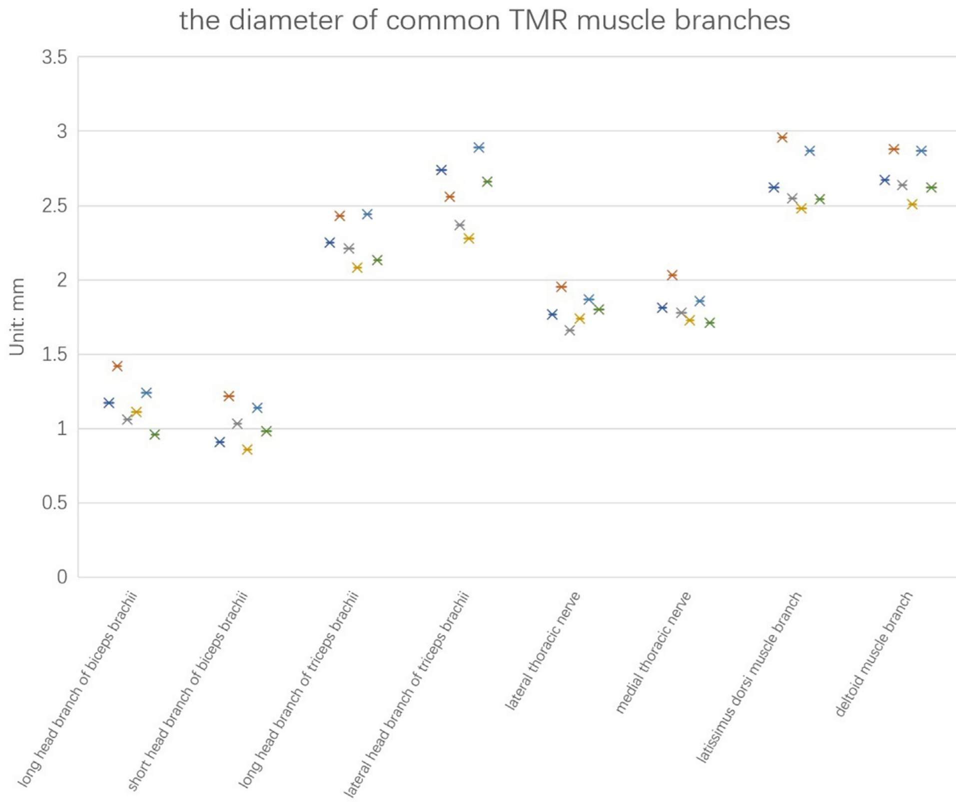

Fig. 6. Diameter of common TMR target muscle branches: long head branch of the biceps brachii, short head branch of the biceps brachii, long head branch of the triceps brachii, lateral head branch of the triceps brachii, lateral pectoral nerve, medial pectoral nerve, latissimus dorsi muscle branch, and deltoid muscle branch. (TMR: targeted muscle reinnervation).

and median nerve branches of finger and wrist flexion were located in the radial volar quadrant. Accurate nerve fascicle anastomosis enhances expression of the brain's intentions.

The diameter of the three donor nerve fascicles in our study ranged from 1.80 to 3.03 mm, while the diameter of the common nerve branches of the targeted muscles ranged from 1.80 to 2.70 mm, except for the mean diameter of the branch for the short head of the biceps brachii, which was smaller than the others at 1.02 mm. Our study also confirmed that, after accurate dissection of the functional nerve fascicle, the diameter of the donor nerve fascicle was more consistent with the muscle branch of the targeted muscle, which was convenient for intraoperative end-to-end nerve anastomosis. In addition, precise positioning of functional nerve fascicle of the terminal branches of median and ulnar nerves is also helpful for peripheral nerve surgery in brachial plexus injury reconstruction or spinal cord injury, and lays the anatomical foundation for various types of sensory reconstruction in future studies.

The main limitations of this study were that the small sample size and that only data for the right upper limb were obtained. However, we could use a mirrored symmetrical technique to determine the distribution of functional nerve fascicles in the nerve trunk of the left upper limb. Also, it is known that there is little intraneural plexus formation between nerve fascicles, which makes tracing very difficult, as the dissection is pursued proximally into the upper arm. Fascicle configuration in the nerve is not parallel, as the fascicles change their location within the course of the nerve, which may compromise the results of this study [19]. This was only an anatomical study based on gross inspection, and staining or intraoperative electrostimulation may be required.

Conclusions

We were able to accurately locate the functional nerve bundles of the median, ulnar and radial nerves in the upper arm. The results of this study will help to improve expression of hand function after targeted muscle reinnervation and lay the neuroanatomical foundation for sensory reconstruction.

Ethics approval and consent to participate

This study was carried out in accordance with the Declaration of Helsinki (2000) of the World Medical Association. It was approved by the Ethics Committee of Beijing Jishuitan Hospital (No.201803-21).

Funding

This work was supported by the National Natural Science Foundation of China (81972131) and Beijing Institute of Trauma Orthopedics Foundation (PXM2021_026275_000004).

Author contributions

FL and YY carried out the studies, participated in collecting the data, and drafted the manuscript. BL and MC performed the statistical analysis and participated in its design. QW and WZ participated in the acquisition, analysis, or interpretation of data and drafting of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

All data generated or analyzed during this study are included in this published article.

Acknowledgments

None.

References

[1] Gart MS, Souza JM, Dumanian GA. Targeted muscle reinnervation in the upper extremity amputee: a technical roadmap. J Hand Surg Am 2015;40:1877–88. http://dx.doi.org/10.1016/j.jhsa.2015.06.119.
[2] Oh C, Carlsen BT. New innovations in targeted muscle reinnervation: a critical analysis review. JBJS Rev 2019;7:e3. http://dx.doi.org/10.2106/jbjs.Rvw.18.00138.
[3] Zuo KJ, Willand MP, Ho ES, Ramdial S, Borschel GH. Targeted muscle reinnervation: considerations for future implementation in adolescents and younger children. Plast Reconstr Surg 2018;141:1447–58. http://dx.doi.org/10.1097/prs.0000000000004370.
[4] Planitzer U, Steinke H, Meixensberger J, Bechmann I, Hammer N, Winkler D. Median nerve fascicular anatomy as a basis for distal neural prostheses. Ann Anat 2014;196:144–9. http://dx.doi.org/10.1016/j.aanat.2013.11.002.
[5] Kuiken TA, Dumanian GA, Lipschutz RD, Miller LA, Stubblefield KA. The use of targeted muscle reinnervation for improved myoelectric prosthesis control in a bilateral shoulder disarticulation amputee. Prosthet Orthot Int 2004;28:245–53. http://dx.doi.org/10.3109/03093640409167756.
[6] Kuiken T. Targeted reinnervation for improved prosthetic function. Phys Med Rehabil Clin N Am 2006;17:1–13. http://dx.doi.org/10.1016/j.pmr.2005.10.001.
[7] Dumanian GA, Ko JH, O'Shaughnessy KD, Kim PS, Wilson CJ, Kuiken TA. Targeted reinnervation for transhumeral amputees: current surgical technique and update on results. Plast Reconstr Surg 2009;124:863–9. http://dx.doi.org/10.1097/PRS.0b013e3181b038c9.
[8] 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;301:619–28. http://dx.doi.org/10.1001/jama.2009.116.
[9] Hoyt BW, Gibson JA, Potter BK, Souza JM. Practice patterns and pain outcomes for targeted muscle reinnervation: an informed approach to targeted muscle reinnervation use in the acute amputation setting. J Bone Joint Surg Am 2021;103:681–7. http://dx.doi.org/10.2106/jbjs.20.01005.
[10] Pierrie SN, Gaston RG, Loeffler BJ. Targeted muscle reinnervation for prosthesis optimization and neuroma management in the setting of transradial amputation. J Hand Surg Am 2019;44:525.e1–8. http://dx.doi.org/10.1016/j.jhsa.2018.11.019.
[11] Ives GC, Kung TA, Nghiem BT, Ursu DC, Brown DL, Cederna PS, et al. Current state of the surgical treatment of terminal neuromas. Neurosurgery 2018;83:354–64. http://dx.doi.org/10.1093/neuros/nyx500.
[12] Dumanian GA, Potter BK, Mioton LM, Ko JH, Cheesborough JE, Souza JM, et al. Targeted muscle reinnervation treats neuroma and phantom pain in major limb amputees: a randomized clinical trial. Ann Surg 2019;270:238–46. http://dx.doi.org/10.1097/sla.0000000000003088.
[13] Hargrove LJ, Miller LA, Turner K, Kuiken TA. Myoelectric pattern recognition outperforms direct control for transhumeral amputees with targeted muscle reinnervation: a randomized clinical trial. Sci Rep 2017;713840. http://dx.doi.org/10.1038/s41598-017-14386-w.
[14] Mioton LM, Dumanian GA, Shah N, Qiu CS, Ertl WJ, Potter BK, et al. Targeted muscle reinnervation improves residual limb pain, phantom limb pain, and limb function: a prospective study of 33 major limb amputees. Clin Orthop Relat Res 2020;478:2161–7. http://dx.doi.org/10.1097/corr.0000000000001323.
[15] Morgan EN, Kyle Potter B, Souza JM, Tintle SM, Nanos 3rd GP. Targeted muscle reinnervation for transradial amputation: description of operative technique. Tech Hand Up Extrem Surg 2016;20:166–71. http://dx.doi.org/10.1097/bth.0000000000000141.
[16] Renninger CH, Rocchi VJ, Kroonen LT. Targeted muscle reinnervation of the brachium: an anatomic study of musculocutaneous and radial nerve motor points relative to proximal landmarks. J Hand Surg Am 2015;40:2223–8. http://dx.doi.org/10.1016/j.jhsa.2015.07.030.
[17] Anderson SR, Wimalawansa SM, Roubaud MS, Mericli AF, Horne BR, Valerio IL. Targeted muscle reinnervation following external hemipelvectomy or hip disarticulation: an anatomic description of technique and clinical case correlates. J Surg Oncol 2020;122:1693–710. http://dx.doi.org/10.1002/jso.26189.
[18] Salminger S, Sturma A, Roche AD, Mayer JA, Gstoettner C, Aszmann OC. Outcomes, challenges, and pitfalls after targeted muscle reinnervation in high-level amputees: is it worth the effort? Plast Reconstr Surg 2019;144:1037e–43e. http://dx.doi.org/10.1097/prs.0000000000006277.
[19] Sunderland S. The intraneural topography of the radial, median and ulnar nerves. Brain 1945;68:243–99. http://dx.doi.org/10.1093/brain/68.4.243.