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RESEARCH ARTICLE

Transfer of the extensor indicis proprius branch of posterior interosseous nerve to reconstruct ulnar nerve and median nerve injured proximally: an anatomical study

Pei-ji Wang[*,#], **Yong Zhang**[#], **Jia-ju Zhao, Ju-pu Zhou, Zhi-cheng Zuo, Bing-bing Wu**
Department of Hand and Foot Surgery, Second Affiliated Hospital of Soochow University, Suzhou, Jiangsu Province, China

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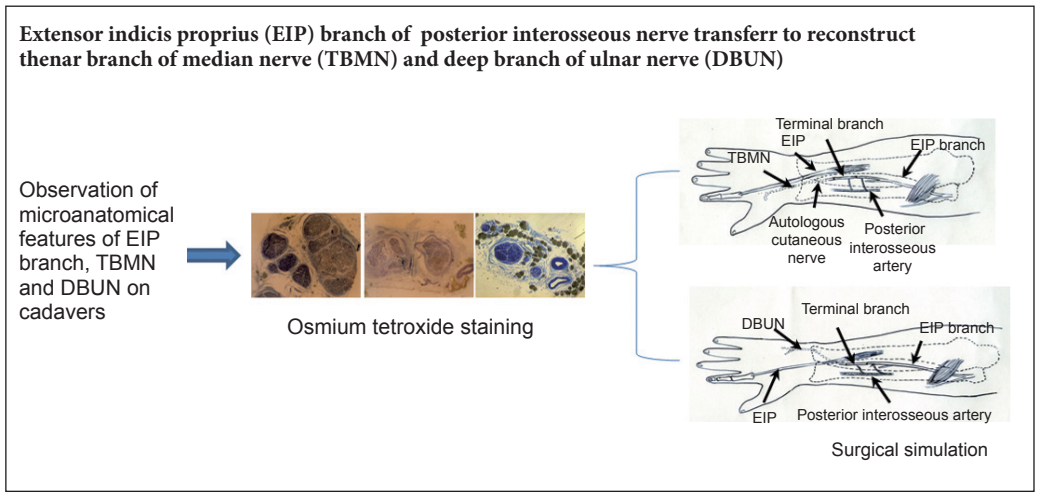
Graphical Abstract



Correspondence to:
Pei-ji Wang, M.D.,
wangpeiji88@163.com.

#These authors contributed equally to this study.

orcid:
0000-0001-6131-2030
(Pei-ji Wang)

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Abstract

Proximal or middle lesions of the ulnar or median nerves are responsible for extensive loss of hand motor function. This occurs even when the most meticulous microsurgical techniques or nerve grafts are used. Previous studies had proposed that nerve transfer was more effective than nerve grafting for nerve repair. Our hypothesis is that transfer of the posterior interosseous nerve, which contains mainly motor fibers, to the ulnar or median nerve can innervate the intrinsic muscles of hands. The present study sought to investigate the feasibility of reconstruction of the deep branch of the ulnar nerve and the thenar branch of median nerve by transferring the extensor indicis proprius branch of the posterior interosseous nerve obtained from adult cadavers. The results suggested that the extensor indicis proprius branch of the posterior interosseous nerve had approximately similar diameters and number of fascicles and myelinated nerve fibers to those of the deep branch of ulnar nerve and the thenar branch of the median nerve. These confirm the feasibility of extensor indicis proprius branch of posterior interosseous nerve transfer for reconstruction of the deep branch of the ulnar nerve and the thenar branch of median nerve. This procedure could be a novel and effective method for the functional recovery of the intrinsic muscles of hands after ulnar nerve or median nerve injury.

Key Words: *nerve regeneration; posterior interosseous nerve; ulnar nerve; median nerve; extensor indicis proprius; thenar branch; nerve transfer; neural regeneration*

Introduction

Proximal injuries of the ulnar nerve or median nerve are commonly seen in the clinic. Although sensation is restored in most cases, recovery of the motor function in the intrinsic muscles of the hand is usually poor, whether the injured nerve is repaired by traditional neurorrhaphy or nerve grafts (Hundepool et al., 2015; Tang et al., 2016). This failure is principally the result of misconnection of the different functional branches and misdirection of the regenerated nerve fibers after anastomosing of the injured nerve directly (Gordon et al., 2008). Another factor is the distance between the repair site and the receptor (intrinsic muscles of hand) is too far to be reinnervated. During the many months required for the regenerating axons to traverse this gap, the denervated muscles undergo irreversible atrophy and degeneration (Chao et al., 2013; Phillips et al., 2014). Prevention of intrinsic muscle atrophy and degeneration after proximal ulnar nerve or median nerve injury is still a challenging problem in the field of hand surgery.

A traditional method of reconstructing intrinsic muscle satisfactorily is the dynamic method of tendon transfer (Seiler et al., 2013; Jia et al., 2015). However, it is difficult to assess the tension on the tendon when it is surgically reattached. Intrinsic palsy of the ulnar or median nerve is probable with extrinsic palsy or tendon lesions suggesting tendon transfer is not feasible (Wang and Zhu, 1997).

Nerve transfer as a treatment has been described to restore function to the denervated muscle in peripheral nerve injuries. To the best of our knowledge, Wang et al. (1997) were the first to study the feasibility of the transfer of the pronator quadratus branch of the anterior interosseous nerve (AION) to the thenar branch of the median nerve (TBMN) and the deep branch of the ulnar nerve (DBUN). They reported good results in a series of twenty patients and showed restoration of the functions of the intrinsic muscles. Studies on cadavers revealed that the DBUN, TBMN and AION had approximately the same number of axons and were of similar diameter, making it feasible to suture the nerves together satisfactorily. Transfer of the AION to the motor branch of the median and ulnar nerve should greatly reduce the delay in reinnervation of the intrinsic muscles and lead to an improved outcome (Wang and Zhu, 1997; Ustün et al., 2001).

In this study, we transfer the extensor indicis proprius (EIP) branch of the posterior interosseous nerve (PION) with the vascular pedicle and connect them to the DBUN and TBMN. This reconstruction was supported by microanatomical measurements and provides a novel method for the functional recovery of an intrinsic muscle of the hand.

Materials and Methods

Materials

This study used nine fresh cadaver specimens that had been prepared for educational use by the medical students in the Department of Anatomy, University of Soochow, China. The specimens were supplied as 18 adult upper extremities (8 male cases, 1 female case). The average age of the cadavers at death was 67 years (range: 44 to 85 years). The examined regions had no history of surgical procedures, trauma, or vascular disease. The use of experimental cadaver specimens was approved by the Ethics Committee of the Second Affiliated Hospital of Soochow University, China.

Surgical simulation

Anastomotic patterns of the vascularized EIP branch of PION with the DBUN and TBMN were designed and simulated on the upper extremities of fresh adult cadaverous specimens.

Observation of microanatomy

The DBUN, TBMN, and EIP branch of PION were fully exposed under a microscope at 10× magnification (Shanghai Optical Instrument Factory, Shanghai, China). The EIP branch of PION was severed 9.5 ± 2.3 cm above the plane of the radial styloid process, at the level of the nerve entry point. The DBUN and the TBMN were severed 1.2 ± 0.8 cm and 6.0 ± 1.3 cm above the wrist respectively, after being separated atraumatically. The diameter of the nerve trunk, the number of myelinated nerve fibers, the atraumatic and forced interfascicular dissection length, the distance between nerve entry point of the EIP branch of the PION to the proximal stump of the DBUN and TBMN after atraumatic dissection were all measured.

Osmium tetroxide staining

After fully exposing and dissecting the EIP branch of PION, the DBUN and the TBMN, a 5-mm nerve section was cut from each nerve stump. The nerve specimens were washed in phosphate-buffered saline and fixed in 4% paraformaldehyde for 12 hours at 4°C, rinsed briefly under running tap water, stained with 1% osmium tetroxide (Electron Microscopy Sciences, Washington, USA) for 12 hours, and rinsed briefly again under running water. The tissue was then dehydrated through a graded alcohol series, cleared, embedded in paraffin, and sliced into 5-μm-thick transverse sections. The sections were mounted, dried by baking, dewaxed, mounted in neutral resin, and viewed under a light microscope (Leica, Heidelberg, Germany). Cross-section images of the nerve were obtained and the number of myelinated nerve fibers per visual field (200-fold field) was calculated using image tool 3.0 software (University of Texas Health Science Center, San Antonio, TX, USA). Each section was counted three times, and the mean was calculated.

Statistical analysis

Data are expressed as the mean ± standard deviation. Statistical analyses were conducted using SPSS 17.0 statistics software (SPSS, Chicago, IL, USA). Differences in the anatomical data and the number of myelinated nerve fibers were analyzed by one-way analysis of variance. If there was significant variation, the *post hoc* Tukey *t*-test was used for the comparison between groups. $P < 0.05$ was considered statistically significant.

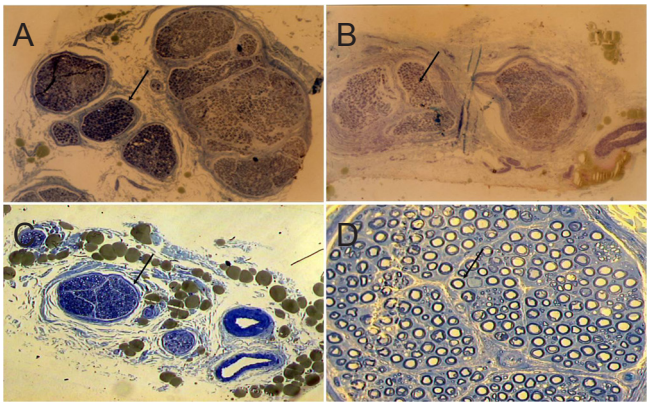

Figure 1 Myelinated nerve fibers of the DBUN, TBMN and the EIP branch of the PION (osmium tetroxide staining).
Myelinated nerve fibers of the DBUN (A, × 40), TBMN (B, × 40) and the EIP branch of the PION (C, × 40; D × 200). Black arrows: Myelinated fibers. DBUN: Deep branch of the ulnar nerve; TBMN: thenar branch of the median nerve; EIP: extensor indicis proprius; PION: posterior interosseous nerve.

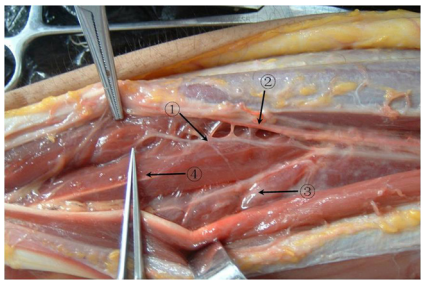

Figure 2 EIP branch of the PION and its concomitant vessels dissected in the forearm.
① EIP branch of the PION; ② branches of posterior interosseous artery; ③ extensor pollicis brevis; ④ extensor pollicis longus. EIP: Extensor indicis proprius; PION: posterior interosseous nerve.

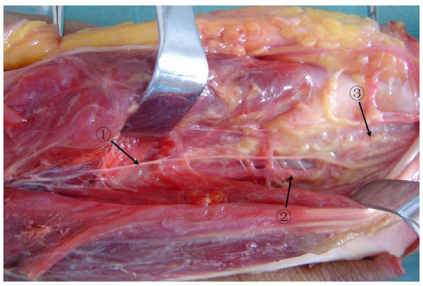

Figure 3 Terminal branch of the PION and its concomitant vessels dissected in the forearm.
① Terminal branch of the PION; ② dorsal perforating branches of the anterior interosseous artery; ③ enlargement of the terminal branches of the PION. PION: Posterior interosseous nerve.

Results

Anatomical characteristics of DBUN

At the wrist, the ulnar nerve crossed superficially to the flexor retinaculum at the radial side of the pisiform bone, where it divided into the superficial and deep branches. DBUN was a terminal, primarily motor branch of the ulnar nerve. The DBUN curved laterally to supply the hypothenar muscles and ran across the palm following the deep palmar arch, and

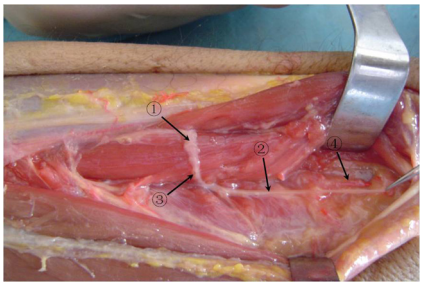

Figure 4 Anastomosis of the EIP branch with terminal branch in the forearm.
① EIP branch; ② terminal branch and its concomitant vessels; ③ anastomotic stoma; ④ dorsal branch of anterior interosseous artery. EIP: Extensor indicis proprius.

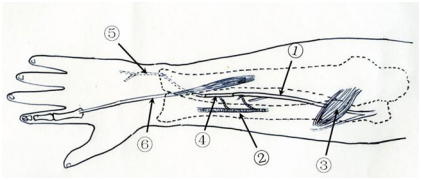

Figure 5 Schematic diagram of the reconstruction of the DBUN.
① EIP branch; ② posterior interosseous artery; ③ supinator muscle; ④ terminal branch; ⑤ DBUN; ⑥ EIP. EIP: Extensor indicis proprius; DBUN: deep branch of the ulnar nerve.

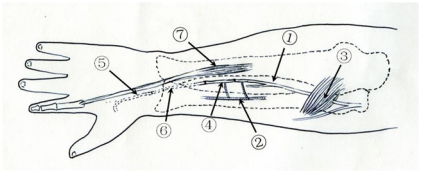

Figure 6 Schematic diagram of the reconstruction of the TBMN.
① EIP branch; ② posterior interosseous artery; ③ supinator muscle; ④ terminal branch; ⑤ thenar branch; ⑥ autologous cutaneous nerve; ⑦ EIP. EIP: Extensor indicis proprius; TBMN: thenar branch of the median nerve.

then terminated in the abductor pollicis muscle. The transverse diameter of the DBUN at the bifurcation was 2.04 ± 0.42 mm. The DBUN contained 2–5 fascicles with 1,342 ± 120 myelinated fibers. The atraumatic dissection length of the superficial and deep branches was 5.04 ± 2.02 cm, and the forced dissection length was 1.60 ± 1.30 cm. At 5.0–7.0 cm proximal portion after the bifurcation, the transverse diameter of the DBUN was 1.86 ± 0.40 mm (**Table 1**; **Figure 1A**).

Anatomical characteristics of TBMN

TBMN was the branch of the median nerve which innervated the intrinsic muscles of the thumb, such as abductor pollicis brevis, opponens pollicis, and the superficial head of the flexor pollicis brevis. It passed distal to the transverse carpal ligament, and terminated in the opponens pollicis. The transverse diameter of the TBMN at the initial site was 1.62 ± 0.36 mm, whereas the transverse diameter of the TBMN at 3.0–4.0 cm proximal portion of the initial site was 1.58 ± 0.24 mm. The TBMN contained 2–4 fascicles with 1,088 ± 95 myelinated fibers. The atraumatic dissectible length of the TBMN was 2.52 ± 0.60 cm, and the forced dissection length

Table 1 Microanatomical parameters of the EIP branch of PION, TBMN and DBUN

	EIP branch of PION (*n* = 18)	TBMN (*n* = 15)	DBUN (*n* = 15)
Fascicles counts (*n*)	1–3	2–4	2–5
Diameters (mm)	1.10±0.24(0.62–2.16)	1.62±0.36(0.73–2.46)	2.04±0.42(0.95–3.87)
Myelinated fibers (*n*)	618±76(439–931)	1,088±95(854–1267)	1,342±120(1041–1609)
Atraumatic dissection length (cm)	–	5.04±2.02(4.22–8.16)	2.52±0.60(1.43–4.89)
Forced dissection length (cm)	–	1.60±1.30(0.82–2.89)	0.50±0.40(0.31–0.93)

Data are expressed as the mean ± SD ranging from minimum to maximum values (min–max) for *n* = 18 upper extremities. EIP: Extensor indicis proprius; PION: posterior interosseous nerve; TBMN: thenar branch of the median nerve; DBUN: deep branch of the ulnar nerve.

was 0.50 ± 0.40 cm (**Table 1**; **Figure 1B**).

Anatomical features of EIP branch and terminal branch of posterior interosseous nerve

The EIP branch originated from the PION at the site 10.90 ± 1.47 cm distal to the lateral epicondyle of the humerus, crossing the extensor pollicis longus along the surface of the EIP, and descending 5.47 ± 0.46 cm into the muscle. It divided into 1–3 branches, mean 1.10 ± 0.30 branches. The transverse diameters of the EIP branch at the initial site and point entering muscle were 1.16 ± 0.20 mm and 1.10 ± 0.24 mm, respectively. It contained a mean number of 618 ± 76 myelinated nerve fibers. Its concomitant vessels were the branch of posterior interosseous vessels (**Table 1**; **Figures 1C**, **D** and **Figure 2**).

The terminal branches of the PION arose after the EIP branching, and descended under the extensor pollicis longus, formed a fusiform enlargement proximal to Lister's tubercle, then traveled through the Lister's tubercle to enter the carpus. The transverse diameter of the terminal branches of the PION at the initial site was 1.08 ± 0.14 mm, and 1.32 ± 0.22 mm at 0.5–0.8 cm proximal to Lister's tubercle. In the distal 1/3 forearm, the terminal branches of the PION were accompanied by dorsal perforating branches of the anterior interosseous artery at 6.34 ± 0.70 cm from the Lister's tubercle (**Figure 3**).

Design and simulated transposition of the EIP branch

Surface projection and incision design

About 75.2% of the course of deep branch of radial nerves was on the line between the condylus lateralis humeri and the malleolus ulnaris, while the EIP branch was about 85.4%, similar to findings of Huang et al. (2002). Therefore, the surface projection of the EIP branch can be regarded as 3/5 distally of the line between the condylus lateralis humeri and the malleolus ulnaris when the forearm was pronated. Consequently, we decided on a dorsal incision in the forearm and a carpometacarpal S-shaped incision.

Dissection of the EIP branch and terminal branch of PION

The EIP branch was carefully dissected. Its concomitant blood vessels and a width of 0.5–1.0 cm fascia were preserved. It was then intersected 9.5 ± 2.3 cm above the malleolus radialis at the nerve entry point. The EIP branch with its concomitant vessels and fascia was freed from its distal to proximal end. The terminal branch was cut at the initial site with concomitant blood vessels and a width of 0.5–1.0 cm fascia preserved, and was dissected approximately 1.0 cm to the distal portion. The nerve and concomitant vessels were cut off at the level about 0.5–1.0 cm proximal to the Lister's tubercle. The nerve was dissected to the proximal end to a length of 5.9 ± 0.8 cm, from where a tunnel to the volar aspect of forearm was made. After atraumatic dissection, the distance from the proximal end of the DBUN or TBMN to the distal end of the transferred EIP branch was 3.40 ± 0.14 cm and 8.60 ± 0.56 cm, respectively.

Anastomosis of the EIP branch with DBUN or TBMN

The distal EIP branch was anastomosed to the proximal terminal branch of PION on the surface of the extensor pollicis longus. The DBUN was dissected atraumatically to the proximal end up to 6.0 ± 1.3 cm above the wrist where it was cut. The distal terminal branch of PION, through the tunnel, was anastomosed to the distal DBUN at the level 6.0 ± 1.3 cm above the volar side of the wrist. The thenar branch was dissected atraumatically and severed 1.2 ± 0.8 cm above the volar side of the wrist. The length of the gap between the distal terminal branch and the proximal thenar branch was 4.02 ± 0.96 cm. Therefore, an autologous nerve was harvested to bridge the terminal branch to the thenar branch through the tunnel (**Figures 4**–**6**).

Discussion

It has been demonstrated that the direct repair of injuries of the median nerve and ulnar nerve occurring proximally usually result in a poor functional outcome, with minimal recovery of intrinsic muscle function. The technique of transfer of the AION to reconstruct the motor component of the median and ulnar nerves has changed the prognosis of such lesions dramatically (Flores, 2011). Previous anatomical studies illustrated that the branch to the pronator quadratus of the AION was suitable for transfer to the motor fascicle of the ulnar and median nerves. Clinical studies reported good recovery of the function of the intrinsic muscles of the hands (Wang and Zhu, 1997; Wang et al., 1997). Based on these studies, we designed a novel method of transferring the EIP branch of the PION to reconstruct the TBMN and the DBUN. The purpose of this study was to investigate the feasibility of this technique.

The PION divides into multiple short branches, one of which is the EIP branch (Elgafy et al., 2000a, b). The EIP

branch is not easily injured because of its deep position in the forearm. All the nerve fibers of the EIP branch are motor fibers, so there should be no competition from sensory fibers for the motor pathways during reinnervation. Therefore it can avoid "fault anastomosis" after anastomosing with the TBMN or terminal branch of PION. If the EIP branch is transferred, the functional loss will be minimal as the extensor digitorum muscle can easily compensate for it. Regeneration of a nerve with a good blood supply is better than those with a poor blood supply (Komatsu et al., 2013; Zhu et al., 2015). Therefore, including a vascular pedicle in the transfer provides a good blood supply, benefitting nerve regeneration and supplying sufficient nutrition to the target muscle to enhance recovery of function.

The results of our anatomical studies demonstrated that the EIP branch of PION is sufficiently similar to either the TBMN or DBUN to allow direct suturing between them. Even though the number of myelinated nerve fiber and the diameter of the EIP branch were slightly less than that of the DBUN and TBMN, it could be compensated during nerve regeneration through generating several lateral branches in the proximal end. This study has confirmed the feasibility of the EIP branch of PION transfer for reconstruction of the DBUN and TBMN anatomically.

This technique is advantageous over direct repair or nerve grafting of proximal injuries, because it shortens the distance for nerve regeneration to the target muscle. Decreasing the distance for reinnervation with the EIP branch transfer will shorten the time frame for nerve regeneration and allow speedier recovery of motor function. The loss of function at the donor site is small and easily compensated for. Moreover, these nerves can be approached by the same incision.

There are limitations to the current study. Wang et al. (1997) reported that using a cutaneous nerve to bridge the defect of the pronator quadratus branch and the thenar branch resulted in a good functional recovery. This confirms that cutaneous nerve graft is feasible. In our study, the defect length from the EIP branch to the proximal end of the DBUN or TBMN is respectively 3.40 ± 0.14 cm or 8.60 ± 0.56 cm. The terminal branch of PION is the sensory nerve which dominates sensation in the posterior region of the wrist and the dorsal hand (Liu et al., 2003; Ay et al., 2005; Jariwala et al., 2014). There are no negative sensory consequences at the donor site following the transfer (Reissis et al., 1992; Inoue et al., 2002; Delclaux et al., 2014). Therefore, using the terminal branch of the PION with the vascular pedicle to bridge the defects of the DBUN or TBMN in the same incision not only repairs the nerve defect, but also benefits nerve regeneration. In reconstructing the thenar branch, the extra 4.02 ± 0.96 cm length of nerve defect has to be repaired by a cutaneous nerve graft. How that extra anastomosis influences nerve regeneration requires further study.

A transferred motor nerve can reinnervate the muscle of the acceptor nerve. However, the recovered function is different from its original one. Sunderland (1974) considered that the central nervous system can readjust to reassign its function. The use of a nerve that supplies co-generic muscles would be preferable to facilitate the repair of the motor nerve injury. The function of EIP is similar to that of the intrinsic muscle. When transferring an EIP branch of the PION to reconstruct the function of intrinsic muscle, the new function can be developed by functional exercise, such as metacarpophalangeal joint flexion, interphalangeal joint extension and metacarpophalangeal joint flexion of thumb.

In this study, we used light microscopy to quantify the number of myelinated nerve fibers in nerve branch cross sections. Recently, some studies comparing light and electron microscopy in the quantitative estimation of peripheral nerves have been performed. It was shown that small myelinated fibers are more easily detected with electron microscopy than with light microscopy (Geuna et al., 2000; Raimondo et al., 2009; Ronchi et al., 2014, 2015). In view of these studies, we suggest that light microscopy is a good starting point for the quantitative investigation of peripheral nerve regeneration. It is easier to perform, requires facilities available to everyone and is less expensive than electron microscopy. However, if significant differences are not detectable with light microscopy, it may be necessary to compare and analyze the measurements with electron microscopy to detect any quantitative differences due to the presence of very small regenerating fibers or unmyelinated fibers (Ronchi et al., 2015).

A couple of aspects are important to note as follows. (1) Sharp dissection of the small nerve should be performed under the microscope. (2) To avoid damaging the nerve and its blood supply it is necessary to include a 0.5–1.0 cm of fascia tissue. (3) In the procedure of nerve transferring, the integrity of tissues should be maintained to avoid separation of the nerve and vessels. (4) A plaster external fixation is needed for 1–2 week to reduce tension of the nerve. (5) Radial nerve injury on the upper arm or forearm is a contraindication of this surgical procedure. Further studies are needed to explore whether nerve transfer procedure is able to benefit patients.

In summary, this procedure has several distinct advantages. Motor function is more likely to be reestablished with the use of a donor nerve that possesses mainly motor fibers. The mean diameter and numbers of fibers of the donor and recipient nerves are similar, and the loss of function is small and easily compensated for. It is feasible to reconstruct the DBUN and TBMN by transferring the EIP branch of the PION with its vascular pedicle. This could be a novel and effective method for the recovery of function of the intrinsic muscles in hands after ulnar nerve or median nerve injury.

Author contributions: *PJW designed this study. YZ wrote the paper, collected and analyzed data. PJW and JPZ established experimental models and observed the anatomic features. JJZ performed histology staining, collected and analyzed data. ZCZ provided literature data. ZCZ and BBW were in charge of paper authorization. All authors approved the final version of the paper.*
Conflicts of interest: *None declared.*
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