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Free Functional Muscle Transfer in Brachial Plexus Injury Patients With Subclavian Artery Injury Using Arteriovenous Loop Grafts

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ABSTRACT

Background: Free functional muscle transfer (FFMT) for brachial plexus injury (BPI) requires adequate donor arterial flow for successful anastomosis. However, concomitant BPI and subclavian artery injury are not uncommon. Arteriovenous (AV) loop graft is one of the methods used to extend vessels to areas with vascular depletion. This case series aims to report the feasibility and outcomes of AV loop grafts for FFMT in BPI patients with subclavian artery injury.

Patients and Methods: This longitudinal descriptive report included adult patients with BPI and concomitant subclavian artery injury. Patients with adequate intra-operative thoracoacromial and/or thoracodorsal arterial flow, sufficient for FFMT without the need for an AV loop graft, were excluded.

Results: Of the 10 initially enrolled patients, three were excluded: two for adequate intra-operative arterial flow, and one for extensive adhesions around the external jugular vein, precluding the index surgery. Seven patients, with a median age of 37 years, mostly male and injured in motorcycle accidents, were included. Four patients underwent a single-stage operation (AV loop graft and FFMT simultaneously), while three patients underwent a two-stage operation. Success rates were 100% for the single-stage operation and 33% for the two-stage operation. The two-stage operation led to increased operative time, extended hospital stays, and anastomosis mismatch challenges. Successful cases regained gracilis muscle motor power for elbow flexion, achieving grade III-IV within 13–29 months.

Conclusion: FFMT with AV loop graft for BPI patients with subclavian artery injury is feasible and effective. Despite complex microsurgical requirements, these procedures significantly restore limb functionality when standard FFMT operations are insufficient.

Trial Registration: ClinicalTrials.gov identifier: NCT06437990

1 | Introduction

Free functional muscle transfer (FFMT) using the gracilis muscle is a standard treatment for late presentation of brachial plexus injuries or failed primary nerve transfer surgeries. However, in patients with multiple unfavorable risk factors that increase the likelihood of primary nerve transfer failure, FFMT can be utilized as an initial intervention to improve function of the disabled limb (Neti et al. 2022). This procedure depends on functional donor vessels, specifically a patent thoracodorsal or thoracoacromial artery from subclavian artery of the injured limb, to supply the muscle flap. However, some brachial plexus injuries are accompanied by subclavian or axillary artery injuries, which compromise the viability of the muscle flap due to insufficient vascular supply. The incidence of vascular injury concomitant to brachial plexus injury is approximately 6%–8% (Neti et al. 2022; Laohaprasitiporn et al. 2018). This concomitant injury, particularly in cases with late presentation of BPI, increases the risk of flap failure or the inability to perform FFMT.

In cases where recipient vessels are damaged or pedicle length is insufficient due to injury, several procedures for pedicle extension are available. Common methods for vascular extension include arteriovenous (AV) loops, vein grafts, and arterial grafts. These techniques are based on microsurgery principles, specifically aiming for a tension-free anastomosis.

The most common technique for pedicle extension is a vein graft. However, it should only be used when the flow rate between the recipient and donor vessels is compatible. An arterial graft can be utilized when a different caliber or higher quality graft is required to match the flap or recipient vessels. A report documented the successful utilization of facial artery as a donor vessel for revascularization in FFMT procedures in BPI patients with subclavian and/or axillary artery injuries (Bhatia, Prabhune, and Carvalho 2020). AV loops bring recipient vessels closer to the defect, reducing the required pedicle length from the flap. They serve as a conduit between a local artery and vein, creating an extension loop that is then divided, extending both the arterial and venous ends to enable microvascular anastomosis (Soto et al. 2023).

Arteriovenous loop grafts have been employed to extend donor vessels to the flap and have been used in various body regions, including the upper extremity. (Soto et al. 2023; Anderson et al. 2021; Angel et al. 1993; Cavadas 2008; Marchesini et al. 2020; Silveira and Patricio 1993; Tremp et al. 2020) Despite their widespread use, AV loop grafts have not been previously utilized in FFMT for late presentation of brachial plexus injuries with concurrent subclavian or axillary artery injuries. This report aimed to assess the feasibility of this surgical technique and report the long-term outcomes of the procedure.

2 | Patients and Methods

The protocol received approval from the institutional review board overseeing research involving human subjects (COA no. Si 691/2013) and was registered with ClinicalTrials.gov (NCT06437990). All participants provided written informed consent, and the report adhered to the principles outlined in the Declaration of Helsinki.

This research was conducted at a tertiary care hospital from 2014 to 2020. We included patients aged 20 years or older who presented with BPI of more than 12 months duration or had unsuccessful primary nerve transfer surgery, accompanied by subclavian or axillary artery injury. The concomitant arterial injury was confirmed by a computed tomography angiogram. However, we excluded patients who had a patent thoracoacromial or thoracodorsal artery with the sufficient flow during donor artery dissection for FFMT. Additionally, we excluded patients in whom the common carotid artery or external jugular vein could not be identified due to significant fibrosis or previous radiation in the neck area.

2.1 | Surgical Technique

Gracilis muscle is the most commonly used donor muscle in FFMT surgery to restore biceps function, which is the top priority for functional reconstruction, particularly in patients with pan-plexus injuries (Doi et al. 2000). Over time, the tendon part of the gracilis muscle, which is longer than the original biceps muscle, was adapted to pass in front of the elbow and be attached to the tendon in the forearm. This could be the tendon of the wrist extensor, finger extensor, or finger flexor, to achieve the desired function and enable the transferred muscle to perform two functions. In this article, we primarily focused on the application of gracilis muscle transfer to restore elbow flexion function, with secondary functions targeting either the wrist extensors or finger flexors.

In the first stage of FFMT surgery, the gracilis muscle was utilized to replace the biceps muscle. Consequently, the thoracoacromial artery, located within the deltopectoral groove, was commonly chosen as the donor blood vessel. The donor nerve was typically selected from the supraclavicular area, with the phrenic nerve or the spinal accessory nerve being frequently utilized.

A donor artery was considered non-viable for standard FFMT surgery if it appeared flaccid, with no visible pulsation and no pulsating blood flow after transection. Therefore, an AV loop operation was considered to lengthen the donor artery and vein from the neck region, utilizing the common carotid artery and external jugular vein as the donor vessels.

2.2 | AV Loop Graft Creation, Vascular Anastomoses and Nerve Transfer to the Gracilis Muscle

The AV loop graft in this report was performed either in a single stage or in two stages.

2.2.1 | Stage 1

The first stage involved creating an AV loop using the lesser saphenous vein harvested from either the left or right leg of the patient. This loop was constructed between the common carotid artery and the external jugular vein. The anastomosis between the common carotid artery and the lesser saphenous vein was performed using an end-to-side technique, while the anastomosis between the lesser saphenous vein and the external jugular vein (or a superficial vein) was performed using an end-to-end technique. The length of the newly created AV loop was designed to be sufficient for the subsequent surgery, which involved the transfer of the gracilis muscle. After verifying the pulsation of the AV loop graft, all wounds were closed (Figure 1).

2.2.1.1 | Special Considerations. In cases where the patient had previously undergone surgery above the clavicle or had significant scar formation on the same side as the brachial plexus injury, the AV loop graft procedure could be modified. The common carotid artery would potentially be connected to the external jugular vein or a superficial vein on the opposite side using an AV loop graft to ensure the viability and adequate length of the graft for subsequent surgical procedures.

2.2.2 | Stage 2

The second stage of the AV loop graft operation was performed 5–7 days after the initial procedure. The AV loop graft was re-explored to ensure the presence of both arterial and venous pulsation. If the pulsation was confirmed, indicating successful blood flow, the patient would then undergo the subsequent surgery to transfer the gracilis muscle from the leg to the arm. The vascular anastomoses from the AV loop graft to the vessels of gracilis muscle were performed using the branches of the AV loop graft, specifically the lesser saphenous vein graft, to ensure proper size matching for the anastomoses. However, the gracilis artery was typically anastomosed to a branch of the AV loop graft using an end-to-end technique (Figure 2). In contrast, the gracilis veins could be anastomosed to either the AV loop graft or its branches (Figure 3). Subsequently, the AV loop was divided to separate the arterial inflow from the venous outflow (Figure 4).

The two-stage operations could be consolidated into a single procedure. After confirming the patent vascular blood flow of the AV loop graft, the gracilis muscle was transferred from the patient's leg to the arm during the same operation.

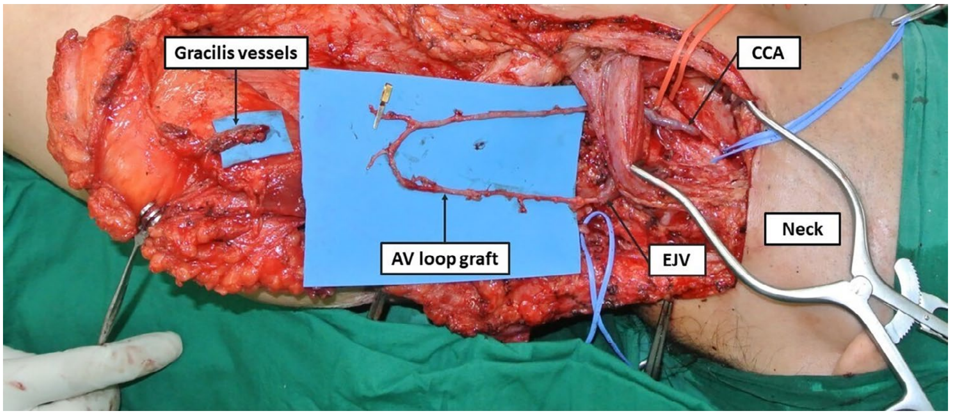

FIGURE 1 | The creation of the AV loop graft showed patent blood flow from the common carotid artery to the external jugular vein. This AV loop graft potentially extends the blood flow from the neck area to the distal clavicle area. (AV, Arteriovenous; CCA, Common carotid artery; EJV, External jugular vein.

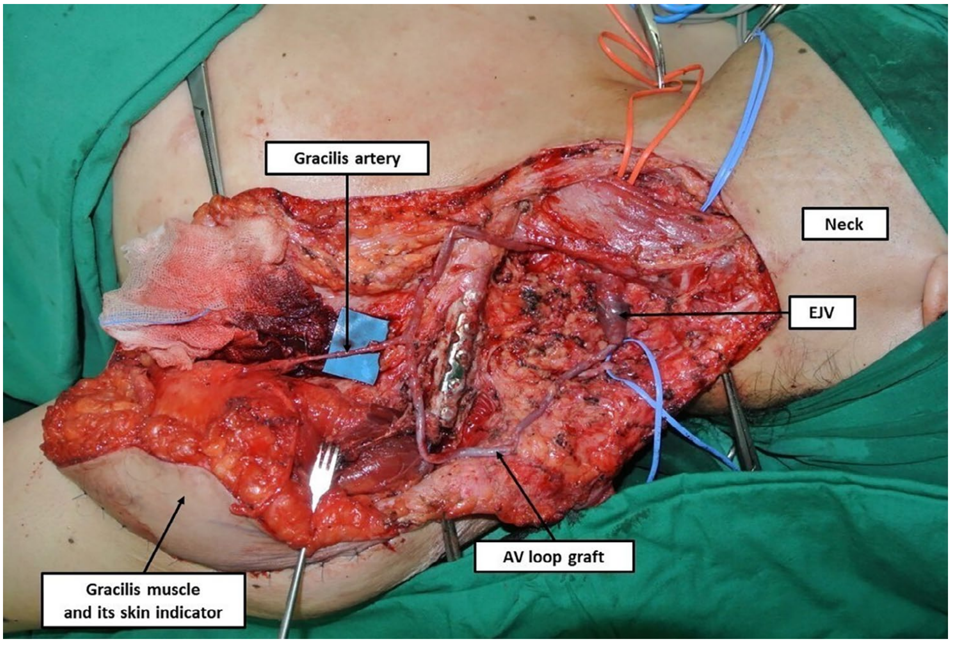

FIGURE 2 | An end-to-end anastomosis of the gracilis artery to a branch of AV loop graft was performed (AV, Arteriovenous; EJV, External jugular vein).

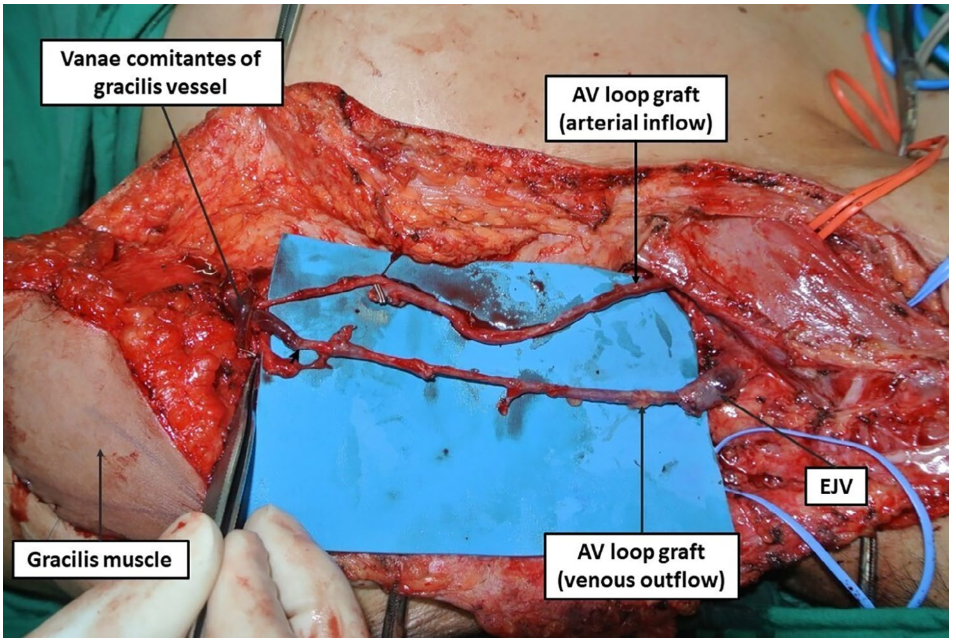

FIGURE 3 | The venae comitantes or the gracilis veins can be anastomosed to either the AV loop graft or its branches, depending on the size of the anastomoses, which drain the venous blood into the external jugular vein. Subsequently, the AV loop is divided to separate the atrial inflow from the venous outflow (AV, Arteriovenous; EJV, External jugular vein).

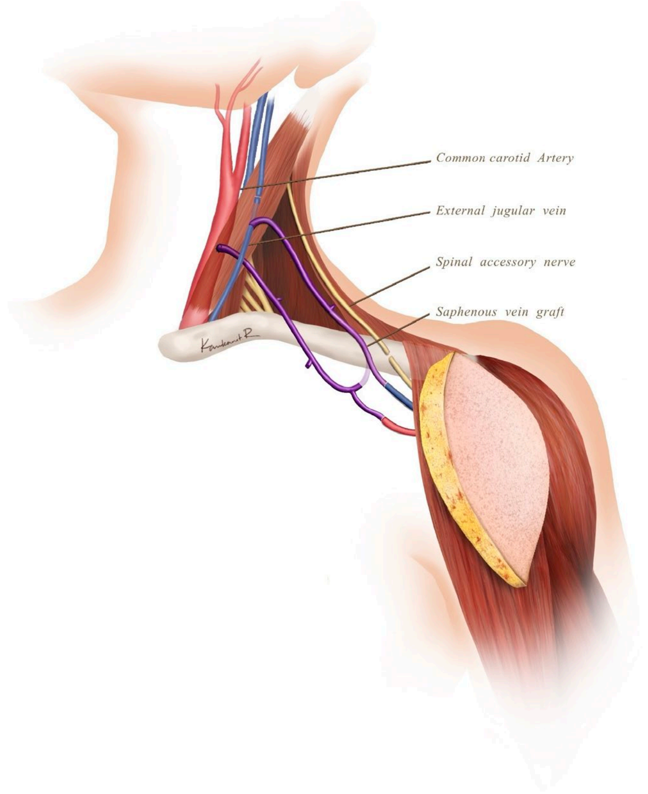

FIGURE 4 | The illustration depicts the anastomosis procedure between donor vessels and gracilis vessels utilizing an AV loop graft.

Finally, the spinal accessory nerve was dissected and harvested during the free gracilis transfer surgery for elbow flexion. This nerve is commonly used as a donor nerve and is transferred to the gracilis nerve (Figure 5).

2.3 | Origin, Pulley, and Insertion of Free Gracilis Muscle Transfer

In the first stage of free gracilis muscle transfer surgery to restore biceps muscle function, the origin of the gracilis muscle was established at the distal half of the clavicle. This was achieved by suturing the muscle through approximately 3–4 holes drilled into the clavicle bone.

The distal tendon of the gracilis muscle was passed beneath the original biceps tendon to act as a pulley for elbow flexion. If wrist or finger extension functions were desired, the distal tendon was threaded under the biceps tendon from the medial side and passed underneath the mobile wad muscles to the lateral epicondyle, positioning it at the origin of the original wrist or finger extensor muscles. If finger flexion function was required, the tendon was passed from the lateral side to the medial side of the biceps tendon and distal to the medial epicondyle.

Once the tendon was threaded through the elbow, using the biceps tendon as a pulley, the distal part of the tendon was connected to the extensor carpi radialis brevis (ECRB), extensor digitorum communis (EDC), or flexor digitorum profundus (FDP) tendon to achieve the desired secondary function. However, for finger flexion function, the authors adjusted the insertion point to the flexor digitorum superficialis (FDS) tendon instead of FDP tendon. This adjustment was based on the observation that patients with non-functional intrinsic muscles could not initiate finger flexion from the metacarpophalangeal (MCP) joint. Pulling the FDP tendon caused flexion to start at the distal interphalangeal (DIP) joint, then the proximal interphalangeal (PIP) joint, often leaving the MCP joint too weak to flex, resulting in a fist-like grip with no palm space and making object grasping more difficult.

Therefore, by changing the insertion to the FDS tendon, finger flexion began at the PIP joint and then moved to the MCP joint, creating a more functional grip with space in the palm, which improved object manipulation and grip strength.

2.4 | Tension Setting of FFMT

Following successful vascular anastomosis, the insertion of the gracilis muscle was subsequently connected to its intended secondary function. To set the tension or length between the origin and insertion of the transferred gracilis muscle, it should match the muscle's original resting length. Before detaching the gracilis muscle from its origin and insertion at the leg, marked the muscle surface with vicryl sutures at approximately 5 cm intervals. This helped in maintaining the same length and tension when the muscle was transferred to the arm, ensuring maximum contraction force. However, in practice, the marked muscle sections were often hidden under the skin and not visible during the transfer. Therefore, tension was set as the elbow flexed to approximately 90°–100°, and the wrist extended as much as possible (Figure 6). This method ensured that the transferred muscle

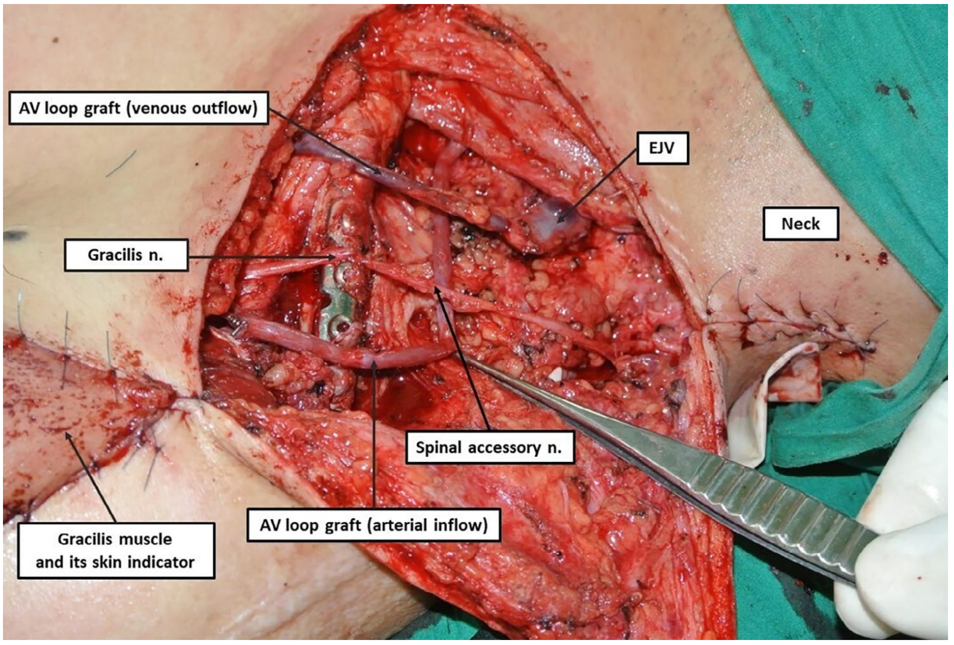

FIGURE 5 | The spinal accessory nerve was used as a donor nerve and transferred to the nerve of the gracilis muscle (AV, Arteriovenous; EJV, External jugular vein; Gracilis n., Gracilis nerve; Spinal accessory n., Spinal accessory nerve).

FIGURE 6 | The tension of the gracilis tendon to the ECRB tendon for elbow flexion and wrist extension functions was set at 90°–100° of elbow flexion with the wrist in maximal extension.

maintained optimal tension and functional capacity in its new location.

During postoperative immobilization, elbow should be flexed to an angle of approximately 90°–100°, with the wrist extended to the maximal tolerable degree, typically around 60°. If the secondary function involved finger flexion, the wrist should be flexed to 10°, with the metacarpophalangeal joints maintained at 90° of flexion, and the proximal and distal interphalangeal joints kept in a neutral, extended position. The operated arm was immobilized in a static elbow and wrist splint for an initial 4-week period. Subsequently, gentle passive range of motion (ROM) exercises were initiated, and the arm was further immobilized in a sling for an additional 4 weeks.

3 | Results

Ten patients were initially enrolled in the report. However, three patients were subsequently excluded from the report. The two excluded patients exhibited adequate thoracoacromial arterial blood flow, which allowed for standard FFMT without requiring the AV loop procedure. Another excluded patient had extensive soft tissue adhesions around the external jugular vein precluded the execution of the ipsilateral AV loop procedure. Therefore, seven patients were included in the report (Table 1). The median age of the patient cohort was 37 years, with an age range of 29–53 years. Five patients were male, and two were female. Three patients underwent surgery on the left side, while four patients underwent surgery on the right side. The average body mass index was 23 kg/m^2, with a range from 16.6 to 29.5 kg/m^2. All patients sustained brachial plexus injuries from motorcycle accidents and had concomitant subclavian or axillary artery injuries. All patients exhibited signs of subclavian or axillary artery occlusion or had reduced vessel caliber as determined by computed tomography angiography. One patient had an upper arm type injury, while the remaining patients had pan-plexus type injuries. The median time from injury to surgery was 48 months, with a range of 15–204 months. Two patients had previously undergone unsuccessful nerve transfer surgery for elbow flexor reconstruction prior to the AV loop procedure. Five patients presented with brachial plexus injuries more than 1 year after injury, rendering them ineligible for nerve transfer surgery. All patients underwent FFMT with the aim of restoring elbow flexion function, utilizing the spinal accessory nerve as the donor nerve.

For the first three patients, a two-stage AV loop procedure was planned, with a 6- to 7-day interval between each stage. The last four patients underwent a single-stage AV loop procedure combined with FFMT surgery (Table 2). The average total operative time for two-staged operations was 573 min, whereas the average total operative time for one-staged operations was 484 min.

All patients underwent reconstruction of the AV loop procedure using a lesser saphenous vein graft. The average length of the vein graft required for anastomosis from the common carotid artery to the external jugular vein was 26 cm, range from 23 to 29 cm. The diameter of the lesser saphenous vein graft ranged from 3 to 4 mm, while the diameter of its branches, used for anastomosis with the gracilis artery, ranged from 2 to 3 mm. The diameter of the gracilis artery ranged from 1.5 to 2 mm, and the diameter of the gracilis vein ranged from 2 to 4 mm.

In the two-staged operations, two out of three patients experienced failed FFMT due to blood clots in the AV loop graft, necessitating the removal of the transferred muscle. One patient developed a urinary tract infection and septicemia following the AV loop grafting procedure, necessitating intravenous antibiotic administration prior to the FFMT operation. Additionally, one patient in the two-staged operation suffered from blood leakage at the common carotid anastomosis site, resulting in a blood loss exceeding 2000 mL. The total length of hospital stay ranged from 16 to 17 days. A successful two-staged operation patient exhibited gracilis muscle motor power of Medical Research Council (MRC) grade 3 at final follow-up, 13 months post-operation.

Four patients were included in a one-stage operation. All patients underwent successful FFMT. However, one patient required an additional operation the day following the FFMT to stop the bleeding from the transferred gracilis muscle. The average blood loss for the one-stage operation was 580 mL. The length of hospital stay ranged from 8 to 9 days. Unfortunately, one patient who underwent one-stage operation was lost to follow-up 2 weeks postoperatively and could not be contacted for detailed outcome assessment. Three out of the four patients achieved gracilis motor power for elbow flexion of MRC grade 3–4 at the last follow-up, which ranged from 10 to 29 months postoperatively.

4 | Discussion

This report is the first to document the use and feasibility of an AV loop graft for FFMT in a brachial plexus patient with concurrent subclavian artery injury, which precludes the standard FFMT operation to restore limb function. The AV loop graft was utilized to extend donor vessels from a distant location to the recipient vessels. Specifically, the anastomosis involved the common carotid artery and external jugular vein, extending to the area near the distal clavicle, facilitating the FFMT for elbow flexion. Despite documented subclavian or axillary artery injuries, a standard exploration of the thoracoacromial trunk or thoracodorsal vessels should be conducted to assess their viability for a standard FFMT without an AV loop graft. If the vessels exhibit insufficient blood flow or are surrounded by extensive adhesions, an AV loop graft can be implemented to supply adequate vascularization to the flap, avoiding an inappropriate site for vascular anastomosis.

The interval between the first and second stages of an AV loop graft for FFMT typically spans approximately 7 days. This period allows the vein graft to enlarge and thicken. The authors observed that performing the anastomosis to the gracilis vessel during the second operation was more challenging. The enlarged vein graft facilitated the overflow of arterial blood to the gracilis muscle. A prolonged maturation period may increase the risk of thrombosis and result in vessel caliber mismatch due to the substantial enlargement of the AV loop (Cavadas 2008; Brüner et al. 2004; Ritter et al. 1996). Furthermore, the two small venae comitantes of the gracilis veins were insufficient for venous drainage, potentially resulting in flap congestion and failure.

TABLE 1 | Demographic data of study participants.

	Study participants						
Demographic data	**No. 1**	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**
Age (year)	37	53	29	37	47	39	29
Sex	Female	Female	Male	Male	Male	Male	Male
Affected side	Left	Right	Left	Right	Right	Right	Left
BMI (kg/m^2)	26.3	23.3	20.2	16.6	21	29.5	24.5
Underlying disease	Epilepsy	None	None	None	None	None	None
Mechanism of injury	Blunt injury; motorcycle accident	Blunt injury; motorcycle accident	Blunt injury; motorcycle accident	Blunt injury; motorcycle accident	Blunt injury; motorcycle accident	Blunt injury; motorcycle accident	Blunt injury; motorcycle accident
Associated injury	Forearm fracture, Shoulder dislocation	Scapular fracture	Scapular fracture, Femoral shaft fracture	None	None	Humeral neck fracture	Clavicle fracture
Subclavian or axillary injury	Occlusion of subclavian artery	Small caliber of axillary artery	Small caliber of axillary artery	Occlusion of subclavian and axillary arteries	Occlusion of subclavian artery	Occlusion of axillary artery	Occlusion of subclavian artery
Previous brachial plexus surgery	None	None	None	Failed primary nerve transfer (PHR-NTB)	None	Failed primary nerve transfer (PHR-NTB)	None
Interval from injury to AV loop surgery (month)	60	108	36	72	204	25	15

Abbreviations: AV loop, arteriovenous loop; BMI, Body mass index; NTB, nerve to biceps; PHR, phrenic nerve.

TABLE 2 | Detailed surgical techniques and outcomes.

Surgical techniques and outcomes	Study participants						
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6	No. 7
Single stage or two stages AV loop surgery	Two stages	Two stages	Two stages	One stage	One stage	One stage	One stage
Operative time (minute)	First stage: 240 Second stage: 305	First stage: 140 Second stage: 405	First stage: 135 Second stage: 490	370	335	490	442
Blood loss (ml)	530	410	2080	350	650	800	520
Length of hospital stay (day)	17	16	17	9	8	9	8
Type of vein graft	Lesser saphenous vein	Lesser saphenous vein	Lesser saphenous vein	Lesser saphenous vein	Lesser saphenous vein	Lesser saphenous vein	Lesser saphenous vein
Length of vein graft (cm)	25	25	29	29	23	26.5	26
Diameter of vein graft (mm)	4	4	4	3.5	3	3.5	3
Diameter of vein graft branches (mm)	3	3	3	3	2.5	2	2
Diameter of gracilis artery (mm)	2	2	1.5	2	1.5	2	1.5
Diameter of gracilis vein (mm)	3	3	3	2	4	3	2
Gracilis origin	Distal clavicle	Distal clavicle	Distal clavicle	Distal clavicle	Distal clavicle	Distal clavicle	Distal clavicle
Gracilis pulley	Biceps tendon	Biceps tendon	Biceps tendon	Biceps tendon	Biceps tendon	Biceps tendon	Brachioradialis muscle
Gracilis insertion	FDS	ECRB	EDC	FDS	ECRB	FDS	ECRB

(Continues)

TABLE 2 | (Continued)

Surgical techniques and outcomes	Study participants						
	No. 1	**No. 2**	**No. 3**	**No. 4**	**No. 5**	**No. 6**	**No. 7**
Donor nerve	Spinal accessory nerve	Spinal accessory nerve	Spinal accessory nerve	Spinal accessory nerve	Spinal accessory nerve	Spinal accessory nerve	Spinal accessory nerve
Success or failed surgery	Failed	Success	Failed	Success	Success	Success	Success
Cause of failure	Blood clot in AV loop	—	Blood clot in AV loop	—	—	—	—
Complications	Urinary tract infection with septicemia	—	Leakage of external carotid artery anastomosis	Bleeding from gracilis muscle required operation to stop bleeding	—	—	—
Final follow-up (month)	—	13	—	29	15	10	0.5
Elbow flexion motor power (MRC)	—	Grade III	—	Grade IV	Grade IV	Grade III	N/A
Secondary function motor power (MRC)	—	WE Grade III	—	FF Grade II	WE Grade I	FF Grade 0	N/A

Abbreviations: AV loop, arteriovenous loop; ECRB, extensor carpi radialis brevis; EDC, extensor digitorum communis; FDS, flexor digitorum superficialis; FF, finger flexion; MRC, Medical Research Council; N/A, not assessed; WE, wrist extension.

The authors therefore recommend performing a single-stage operation, which facilitates easier vascular anastomosis, reduces the total operative time, shortens hospital stay, and yields more promising results. However, a two-team dissection approach is advised, with one team dedicated to vein graft harvest and creation of AV loop, and another team focused on gracilis muscle harvest.

Our results align with the meta-analysis and retrospective study comparing single-stage and two-stage AV loop procedures. The one-stage AV loop graft procedure had significantly fewer major complications and a higher success rate compared to the two-stage procedure (Knackstedt et al. 2018; Lin et al. 2004). A systematic review and meta-analysis found similar success rates between one- and two-stage AV loop grafts in lower limb flap reconstruction (Asensio-Ramos et al. 2024). We hypothesize that outcomes may vary by donor artery; using the high-flow common carotid artery as in our technique could contribute to greater graft enlargement and thickening in the second-stage reconstruction. However, the two-stage procedure can be advantageous in specific situations, as it allows for two manageable and controlled operations. This method provides the opportunity to handle each anastomosis separately, which can be advantageous in case of AV loop or flap compromise during either operation. If there are concerns regarding blood flow to the AV loop graft, some surgeons may opt to initially perform the AV loop and subsequently undertake the flap reconstruction at a later stage (Brüner et al. 2004; Henn et al. 2019).

5 | Conclusion

Free functional muscle transfer with arteriovenous loop graft procedures for reconstructing brachial plexus injury patients with concomitant subclavian or axillary artery injury are feasible and yield excellent results. Although, these procedures require complex microsurgical techniques, they are worthwhile for restoring the functionality of a disabled limb previously considered unsalvageable due to the insufficient vascular supply for the standard FFMT operation.

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Ethics Statement

The ethical approval of this study was obtained from the Siriraj Institutional Review Board, Faculty of Medicine Siriraj Hospital, Mahidol University, Bangkok, Thailand (Certificate of Approval no. Si 691/2013).

Consent

Written informed consent was obtained from all subjects before the study.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The datasets used or analyzed during the study are available from the corresponding author on reasonable request.

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