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Functional muscle transfer for restoration of elbow flexion: a review

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Abstract
Elbow flexion is essential to help position the hand in space and for functional use of the upper extremity. Loss of elbow function can be secondary to many etiologies, including but not limited to brachial plexus injury, traumatic muscle loss, oncologic treatment, poliomyelitis or congenital absence of motor function. The end result is a significant functional limitation of the upper extremity. One method to address the loss of elbow flexion is the use of a functional muscle transfer. These transfers can be performed as pedicled rotational transfers or free functional muscle transfers. This article reviews functional muscle transfers for restoration of elbow flexion as a treatment option for patients with an otherwise unreconstructable extremity.

Keywords: Brachial plexus injury, elbow flexion, functional muscle transfer, pedicled latissimus dorsi transfer, free latissimus dorsi transfer, free gracilis transfer

INTRODUCTION
Elbow flexion is considered one of the most important upper extremity motions to accomplish activities of daily living. As such, loss of elbow flexion significantly limits upper extremity function. These injuries may be caused by obstetric or traumatic brachial plexus injuries, elbow flexor muscle loss due to trauma or oncologic resection, brachial plexus damage from oncologic resection or radiation treatment, poliomyelitis,

or congenital loss of elbow motion, as in arthrogryposis. When muscles required for elbow flexion (specifically biceps brachii and brachialis) are viable, nerve transfers or grafts may be an option for restoration of elbow flexion[1,2]. However, in cases of chronic injuries, muscle loss, atrophy, fibrosis, or extensive brachial plexus injury, nerve transfer or graft may not be sufficient to restore elbow flexion. In these cases, muscle transfer options should be considered[1]. Restoration of elbow flexion should be prioritized to restore function to the upper extremity, followed by finger flexion and finger extension[3]. In general, a single transferred muscle should provide a single function, though in the case of severe brachial plexus injury, this may be impossible due to limited numbers of donor nerves[3].

INDICATIONS

A pedicled latissimus transfer for restoration of elbow function was first described by Schottstaedt *et al.* in 1955 and Hovnanian in 1956[4,5]. Since that time, numerous studies have examined various options for functional muscle transfers. Free muscle functional muscle transfers were used by Manktelow and McKee in 1978 and Zuker *et al.* in 1991 to restore upper extremity function[6,7]. As techniques have progressed, functional muscle transfers can now be used for restoration of shoulder flexion, elbow flexion, elbow extension, finger flexion, finger extension, and thumb motion, either in isolation or in combination to restore muscle functions[8-10]

Patients who are being considered for functional muscle transfer must be motivated and willing to perform the extensive postoperative therapy and rehabilitation required for maximizing function. The recipient site requires full passive motion at the joint the transfer will move, in addition to a soft tissue bed conducive to muscle and tendon gliding. Healthy donor nerves and vessels are required. Functional muscle transfer should be used when no nerve or tendon transfer options are available. Patient age is an additional factor to consider -- while children are more likely to have successful restoration of motor function, there may be a mismatch in growth between the transferred muscle and the humerus, potentially leading to elbow contracture as the child reaches skeletal maturity[9]. Stevanovic and Sharpe recommend an age limit of 45 years old for free functional muscle transfers to optimize recovery of motor function[9] However, Doi *et al.* showed success after free functional muscle transfer in patients aged 62 years old and younger, while Ihara *et al.* had successful outcomes up to age 65[11,12]. Additional factors that are detrimental to outcomes, especially in free muscle transfers, include diabetes, vascular disease, cardiac disease, autoimmune conditions, smoking, and obesity[9].

DONOR MUSCLES

Several donor muscle options are available for restoration of elbow flexion. In the setting of vascular compromise from trauma or irradiation, a pedicled latissimus is preferred to restore elbow flexion without the need for an arterial anastomosis. The pedicled transfer is technically less challenging as it does not require a microvascular anastomosis. When a free flap is required, such as in the case of poor ipsilateral latissimus function, the gracilis is the most commonly used donor muscle. The gracilis has a redundant function in the lower extremity, making it more suitable for transfer than other lower extremity donor muscles. Its size and excursion make it ideal for restoration of upper extremity function, where it may be used in the forearm for restoring wrist or digit flexion or extension, or in the upper arm for restoring elbow flexion.

Latissimus dorsi (pedicled)

The latissimus dorsi muscle is a versatile option for restoring elbow flexion. It can be performed as a rotational muscle transfer or free functional muscle transfer from either the ipsilateral or contralateral side. Prior to surgery, the function of the latissimus muscle must be tested to ensure the transferred muscle can adequately power elbow flexion, as described by Stevanovic *et al.*[13]. The latissimus dorsi is evaluated by palpating or gently pinching the muscle at the posterior axillary fold during adduction, extension, and internal rotation of the arm. The patient may also be asked to cough while the clinician holds the posterior axillary fold to palpate muscle contraction. Patients may also perform exercises with a physical therapist prior to surgery to maximize the strength of the latissimus dorsi muscle.

A pedicled transfer has the advantage of not requiring microsurgical anastomoses. The patient is placed in the lateral decubitus position, and the entire upper extremity, along with the lateral side from the shoulder girdle to the pelvis, is included in the surgical field. As described in prior studies, the defect in the anterior arm is measured along with the distance from the proximal aspect of the planned incision to the coracoid. This measurement is used to plan the skin paddle location relative to the axis of rotation to ensure coverage of the arm soft tissue[13]. The incision is made from the posterior axillary fold to the midpoint of the iliac crest, allowing identification and exposure of the latissimus dorsi [Figure 1]. With the latissimus in the stretched position (abduction, forward flexion, and external rotation of the arm), marking sutures may be placed at 5 cm intervals along the latissimus prior to mobilization to use for setting tension at the recipient site[13,14]. The latissimus dorsi muscle is then elevated off the thoracic wall, with care to avoid injury to the thoracodorsal artery pedicle, which enters the muscle 10-12 cm from the axilla[14]. The thoracodorsal nerve is also protected to maintain innervation to the transferred muscle [Figure 2]. The serratus anterior can be elevated along with the latissimus dorsi as a chimeric flap when a larger defect requires coverage, though this is not often the case in the upper extremity[15]. After pedicle mobilization, when a bipolar transfer is planned, the insertion on the humerus is released and sutures are placed in the tendon. In cases where a unipolar transfer is planned, the humeral insertion is left intact[1]. A bipolar transfer has the advantage of allowing proximal fixation to the coracoid, acromion, or lateral clavicle which can provide a more direct line of pull while stabilizing the shoulder[1].

To transfer the muscle to the anterior arm, the latissimus is tubularized. An incision is made over the coracoid, where the origin of the transferred muscle is planned. A subcutaneous tunnel is created connecting the posterior and anterior incisions, and the latissimus tendinous insertion is passed below the pectoralis major tendon to the coracoid where it is secured with sutures or suture anchors [Figure 3]. The remainder of the tubularized latissimus is passed to the anterior arm [Figure 4]. Care must be taken to avoid twisting the pedicle while passing the muscle, which may lead to flap ischemia[14]. To set the tension of the transferred latissimus, the muscle is stretched distally, the elbow is extended, and the distal latissimus is secured to the distal biceps tendon [Figure 5]. Since the marking sutures were placed with the latissimus in extension at the donor site, securing the muscle at the recipient site with the elbow in extension should be performed after re-establishing the 5 cm interval between marking sutures[14]. After securing the muscle, the shoulder and elbow are ranged to ensure there is not excessive tension on the pedicle. After closure, the shoulder is immobilized with an abduction pillow and the elbow is immobilized in 90 degrees of flexion[13,14].

Reported outcomes are shown in Table 1. The majority of patients achieved at least antigravity strength with pedicled latissimus transfer, with a low rate of reported complications. Of the studies reporting motor outcomes, 87% of patients achieved at least antigravity flexion strength. Range of motion was inconsistently reported in the literature. In the publications describing final elbow flexion, all but two reports revealed a mean postoperative elbow flexion of 90° or more.

Latissimus dorsi (free)

A free latissimus dorsi transfer allows more flexibility in use for restoration of elbow flexion, but it is technically more demanding than a pedicled transfer, given the need for microsurgical anastomoses. Either

Table 1. Reported outcomes of pedicled latissimus dorsi transfer. MRC: Medical Research Council muscle grade

Reference	Number of patients	Mean age (years)	Pathology	Elbow flexion MRC < 3	MRC 3	MRC ≥ 4	Mean postop elbow flexion (degrees)	Complications
Chuang *et al.*[16]	10	Not specified	Brachial plexus trauma	0	4	6	NR	None reported
Haas *et al.*[17]	2	20	Upper arm amputation	0	2	0	NR	None reported
Haninec *et al.*[18]	2	Not specified	Brachial plexus trauma	0	0	2	90 to 120	None reported
Kawamura *et al.*[19]	10	16.9	8 brachial plexus trauma 1 birth palsy 1 humeral fracture	0	2	8	111	None reported
Martin *et al.*[20]	4 (6 limbs)	Not specified	4 congenital 2 brachial plexus trauma	1	0	5	115	1 revision for muscle dehiscence 2 donor site seroma
Moneim *et al.*[21]	5	29.4	Brachial plexus trauma	0	1	4	92	None reported
O'Ceallaigh *et al.*[22]	1	35	Electrical burn	0	0	1	80	None reported
Schoeller *et al.*[23]	5	35.5	Upper arm amputation	0	2	3	NR	None reported
Stevanovic *et al.*[13]	4	18	Traumatic anterior compartment defect	0	0	4	134	1 infected hematoma
Vekris *et al.*[24]	9	Not specified	Brachial plexus trauma	0	9 (distribution not specified)		NR	2 skin necrosis and infection, distal insertion revision
Zancolli *et al.*[25]	8	Not specified	2 brachial plexus trauma 6 poliomyelitis	0	0	8	128	None reported
Hirayama *et al.*[26]	7	33.3	Brachial plexus trauma	Not specified4 excellent, 2 good, 1 failure			NR (4 could move hand to mouth)	1 failure (fibrofatty degeneration of transferred muscle)
Rogachefsky *et al.*[27]	1	39	Traumatic anterior compartment defect	NR	NR	NR	135	None reported
Eggers *et al.*[28]	3	32	Brachial plexus trauma	0	0	3	132	None reported
Cambon-Binder *et al.*[29]	7	29	4 traumatic anterior compartment defect 3 brachial plexus trauma	1	1	5	91	None reported
Takami *et al.*[30]	2	22	Brachial plexus trauma	0	0	2	127	None reported
Hochberg *et al.*[31]	1	11	Electric burn	NR	NR	NR	"complete"	None reported
Germann *et al.*[32]	3	28	2 traumatic anterior compartment defect 1 upper arm amputation	1	0	2	105	None reported
Mordick *et al.*[33]	1	16	Traumatic anterior compartment defect	0	0	1	110	None reported
De Moraes *et al.*[34]	6	39	Brachial plexus trauma	1	4	1	73	None reported
Alshammari *et al.*[35]	1	30	Traumatic anterior compartment defect	NR	NR	NR	120	None reported
Lupon *et al.*[36]	1	25	Sarcoma	NR	NR	NR	140	None reported
Kameda *et al.*[37]	1	29	Brachial plexus trauma	0	0	1	135	None reported
Sood *et al.*[38]	1	77	Sarcoma	0	1	0	NR	None reported
Ma *et al.*[39]	20	43	Anterior compartment defect	NR	NR	NR	16 excellent (134)	3 flap edge necrosis and wound

							3 105+ 1 85	breakdown
Minami *et al.*[40]	1	32	Brachial plexus trauma	0	0	1	135	None reported
Bostwick *et al.*[41]	1	Not specified	Musculocutaneous injury, anterior compartment atrophy	0	0	1	"full"	None reported
Botte *et al.*[42]	5	Not specified	3 brachial plexus trauma 1 upper arm amputation 1 arm crush	NR	NR	3	109	Not specified
Stern *et al.*[43]	10	19	3 Erb palsy 3 brachial plexus trauma 1 sarcoma 3 anterior compartment defect	1	3	6	107	1 pedicle twisted and failed

Figure 1. External anatomic landmarks for harvest of the latissimus dorsi flap.

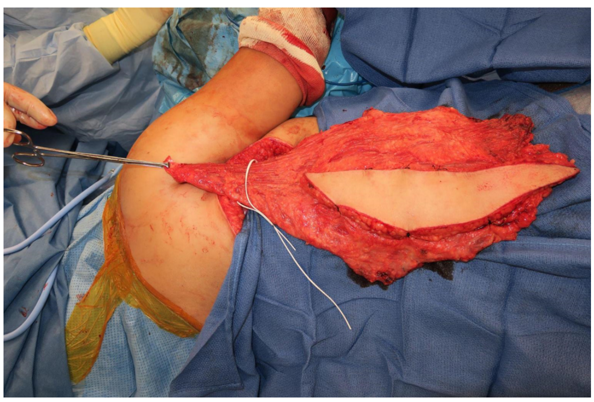

Figure 2. The pedicled latissimus dorsi flap after elevation.

the ipsilateral or the contralateral free latissimus may be used. The contralateral latissimus dorsi muscle is considered in the event of atrophy or injury to the ipsilateral muscle. The approach and surgical dissection are similar to that described for the pedicled rotational latissimus transfer [Figure 6]; however, the patient needs to be repositioned to a supine position after the muscle has been harvested[9]. The latissimus muscle may be neurotized by the distal branch of the spinal accessory nerve, intercostal nerves, contralateral C7

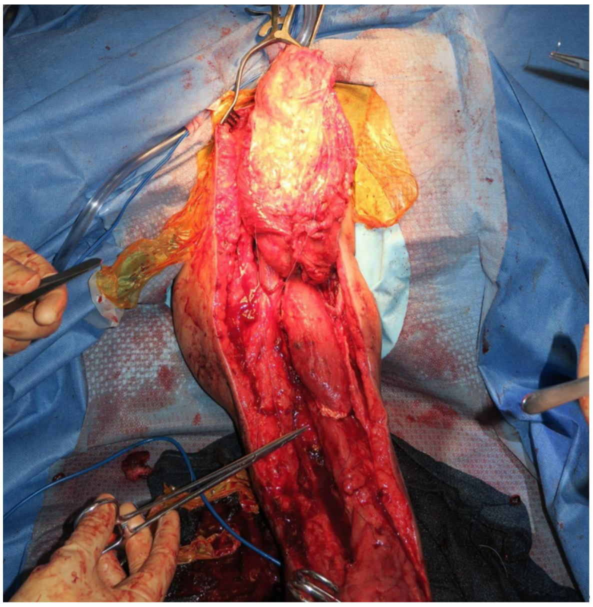

Figure 3. Rotation of the pedicled latissimus dorsi flap to the anterior arm.

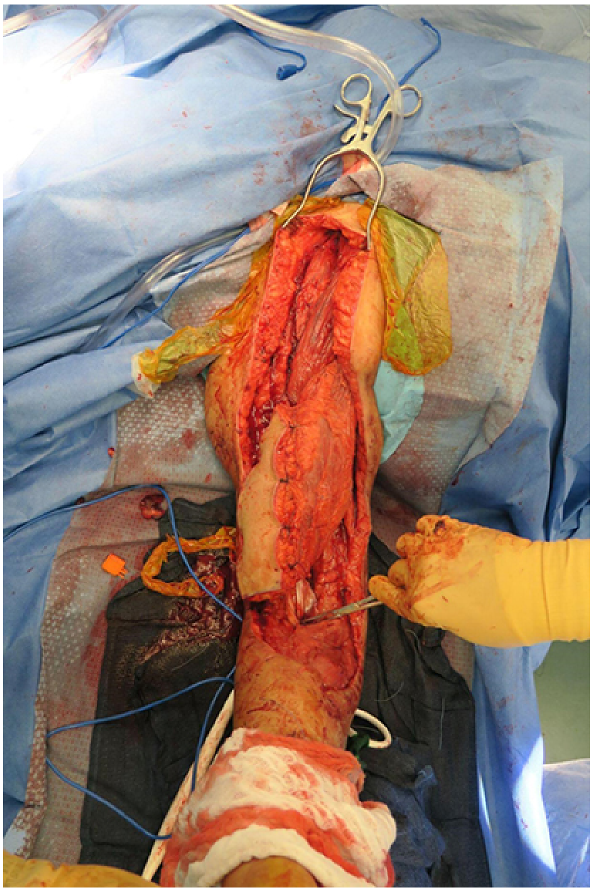

Figure 4. Planned inset of the pedicled latissimus dorsi flap to the anterior arm.

Figure 5. Inset of the pedicled latissimus dorsi flap.

nerve root, contralateral lateral pectoral nerve, or intact ipsilateral cervical nerve roots or intraplexal nerve branches[9,44]. Terzis *et al.* demonstrated increased postoperative mean muscle grade after neurotization of three intercostal nerves compared to two intercostals[44]. The thoracodorsal artery of the transferred latissimus may be anastomosed to the thoracoacromial artery, and the venae comitantes or cephalic vein may be used for venous outflow[9].

Reported outcomes are shown in Table 2. In the studies reporting individual patient motor grades, 83% achieved at least antigravity elbow flexion strength. Mean elbow flexion was 72°.

Gracilis

The gracilis muscle is a commonly used donor muscle for a variety of upper extremity reconstruction indications. Either the ipsilateral or the contralateral gracilis may be used. In cases of double free functional muscle transfer used to restore multiple functions in the extremity, bilateral gracilis can be harvested. However, the direction of the vascular pedicle makes the contralateral gracilis a more desirable option. The gracilis provides knee flexion, internal rotation, and thigh adduction, but is redundant and does not lead to functional deficits in the leg when harvested. Additionally, it may be harvested with a skin paddle, and its length and excursion provide an ideal replacement for elbow flexors. One important aspect to consider when harvesting the gracilis is the short pedicle length. Determining the estimated pedicle length prior to flap harvest is of utmost importance to determine if the gracilis is a viable option. In the event that the pedicle length is insufficient, a vein graft may be utilized.

Table 2. Reported outcomes of free latissimus dorsi transfer. MRC: Medical Research Council muscle grade

Reference	Number of patients	Mean age (years)	Pathology	Neurotization	Vessel anastomosis	Elbow flexion MRC < 3	MRC 3	MRC ≥ 4	Mean elbow flexion (degrees)	Complications
Terzis *et al.*[44]	37	Not specified	Brachial plexus trauma	15 intercostal 7 distal spinal accessory 4 cervical plexus 4 ipsilateral plexus 5 contralateral C7 1 contralateral lateral pectoral	Not specified	Mean muscle grade reported Intercostal 3.33 Distal accessory 3.05 Cervical plexus 2.8 Ipsilateral plexus 2.66 cC7 3.22 Contralateral lateral pectoral 2			NR	2 failures (in 42 transfers for elbow flexion and extension)
Doi *et al.*[45]	4	21	Brachial plexus trauma	Distal spinal accessory	Not specified	0	0	4	90	None reported
Doi *et al.*[46]	3	32	Brachial plexus trauma	Distal spinal accessory	Not specified	0	2	1	83	1 recurrence of nerve palsy
Terzis *et al.*[47]	20	Not specified	Brachial plexus trauma	Not specified	Not specified	NR	NR	NR	NR	3 hematomas 7 seromas
Minami *et al.*[40]	2	Not specified	Brachial plexus trauma	Intercostal nerves (4,5)	Not specified	0	2	0	90	None reported
Botte *et al.*[42]	3	Not specified	Brachial plexus trauma	Not specified	Not specified	2	1	0	23	Not specified

Figure 6. Harvested free latissimus dorsi flap.

The surgical technique for free gracilis transfer has been well described in the literature[3]. The patient is placed in a frog leg position and an incision is created along a line from the pubic tubercle to the medial femoral condyle [Figure 7]. If a skin paddle is used, it is created in the proximal third of the incision and just posterior to the line. The gracilis is the most posterior adductor muscle of the thigh, and is differentiated from the sartorius by its origin on the pubic tubercle, rather than anterior superior iliac spine. The medial thigh fascia is incised and kept with the gracilis muscle to improve independent gliding during contraction. The distal tendon is identified and separated from the other tendons of the pes anserinus. As with the latissimus transfer described above, marking sutures may be used at fixed intervals to help define resting length. Proximally, the neurovascular pedicle is identified 8 to 12 cm distal to the pubic tubercle [Figure 8]. The pedicle is divided after exposure of the recipient site and division of origin and insertion of the muscle to minimize ischemia time[3]. Prolonged ischemia time should be avoided -- Martins-Filho *et al.* demonstrated a trend towards improved results in terms of muscle strength with decreased ischemia time[48]. Additionally, they noted a trend towards poorer functional outcomes with only one venous anastomosis compared to two[48].

The recipient site is prepared with an extensile anterior arm approach including exposure of the lateral clavicle, acromion, and coracoid proximally, and the medial epicondyle and antecubital fossa distally [Figure 9]. The gracilis is attached proximally to the lateral clavicle and acromion or coracoid via suture anchors or bone tunnels. By fixing the muscle proximally first, the muscle can then be stretched to its resting length and the position of arterial anastomosis can be planned to avoid undue tension on the pedicle. Arterial anastomosis may be performed with the thoracoacromial, lateral thoracic, or subscapular arteries in an end-to-end fashion, or the brachial artery in an end-to-side fashion [Figures 10][3]. After anastomosis, distal gracilis is secured to the distal biceps tendon or the radius or ulna, with the restoration of the distance between the previously placed marking sutures while the elbow is held in extension [Figure 11][49]. The orientation of the gracilis may be reversed in the event of prior surgery near the brachial plexus, which allows the anastomosis and nerve coaptation to be performed more distally, out of the region of prior scarring[50,51].The gracilis may also be used for finger flexion when attached distally to the flexor digitorum profundus (FDP) and flexor pollicis longus (FPL), or finger extension when attached distally to the extensor digitorum communis (EDC). Maldonado *et al.* showed that distal tendon attachment (to FDP or FPL tendons with flexor carpi radialis [FCR] tendon autograft) was associated with superior elbow flexion strength and range of motion compared to biceps tendon reattachment[52]. Bertelli showed the gracilis muscle flap can be combined with a Steindler flexorplasty, wherein the flexor-pronator mass origin is transferred proximally to the anterior humerus to improve elbow flexion, to increase strength and decrease time to elbow flexion[51].

Following distal fixation, nerve coaptation is performed. The gracilis may be innervated by a variety of donor nerves, including the distal spinal accessory nerve, intercostal nerves, fascicles of the ulnar or median nerve, the phrenic nerve, or contralateral medial pectoral nerve[3]. In cases where elbow flexion was lost due to anterior compartment trauma or resection, the original musculocutaneous nerve may be used. The authors prefer neurotization with the distal spinal accessory nerve. The spinal accessory nerve is identified after detaching the trapezius insertion from the clavicle and the acromion. The distal branch of the spinal accessory nerve is divided and a coaptation is performed to the motor branch of the gracilis with microsurgical technique.

Reported outcomes are shown in Table 3. The majority of patients, 79% of those reported, achieved antigravity strength or stronger with free gracilis transfer, with a low rate of reported complications.

Table 3. Reported outcomes of free gracilis transfer. MRC: Medical Research Council muscle grade

Reference	Number of patients	Mean age (years)	Pathology	Neurotization	Vessel anastomosis	Elbow flexion MRC < 3	MRC 3	MRC ≥ 4	Mean elbow flexion (degrees)	Complications
Silva *et al.*[53]	87	30	Brachial plexus trauma	45 spinal accessory (4 using sural nerve graft) 10 intercostal nerves (3 with graft) 8 median nerve fascicles 22 ulnar nerve fascicles 2 phrenic nerve	Not specified	32	30	25	NR	3 loss of skin monitoring signal 1 hematoma compressing pedicle 4 infections
Ikuta *et al.*[54]	1	11	Brachial plexus trauma	Intercostal nerves (3, 4)	Lateral thoracic artery, venae comitantes	0	1	0	90	None reported
Krakauer *et al.*[55]	3	30	Brachial plexus trauma	Intercostal nerves (3, 4)	Not specified	1	1	1	72	None reported
Chuang *et al.*[49]	38 (34 gracilis, 4 rectus femoris, results combined)	25	35 brachial plexus trauma 3 traumatic anterior compartment defect	31 intercostal nerves (3 nerves in 23, 2 nerves in 8) 4 glossopharyngeal nerve 3 musculocutaneous nerve (biceps loss, intact plexus)	Lateral thoracic artery or thoracodorsal artery	10 (results combined)		28	NR	None reported
Chuang *et al.*[16]	16	Not specified	Brachial plexus trauma	Intercostal nerves	Not specified	3	6	7	NR	None reported
Barrie *et al.*[56]	22 (15 single gracilis; 7 double gracilis)	25	Brachial plexus trauma	5 spinal accessory 8 intercostal (3, 4) 1 intercostal (4, 5) 1 musculocutaneous 7 combination (spinal accessory and intercostal, double transfers)	7 thoracoacromial 9 brachial 2 axillary 1 lateral pectoral 3 combination (thoracoacromial and brachial)	2	4	16	105	5 failures
Kay *et al.*[57]	33	Median 4.8 (20 children) Median 34 (13 adults)	13 obstetric brachial palsy 12 adult brachial plexus trauma 4 arthrogryposis 2 sarcoma 1 polio 1 radial dysplasia	18 intercostal 12 fascicles of ulnar nerve 2 spinal accessory with graft 1 thoracodorsal	Brachial artery or posterior branch to triceps; vena comitans of brachial artery	6 adults 3 children	7 adults 17 children		NR	3 microvascular failures 6 hematomas 3 infections 1 recipient dehiscence

Sungpet *et al.*[58]	3	28	Brachial plexus trauma	Ulnar nerve fascicle	Brachial artery; cephalic vein	0	0	3	110	None reported
Armangil *et al.*[59]	16	27	Brachial plexus trauma	12 spinal accessory nerve 2 medial pectoral 1 phrenic 1 intercostal (4,5,6)	Thoracoacromial artery, vena comitantes or cephalic vein	5	11		63	2 flap failures
Chen *et al.*[60]	39	27	Brachial plexus trauma	Spinal accessory nerve	Brachial artery, axillary artery, or subclavian artery	2	8	29	107	1 flap failure 1 donor site hematoma
Dodakundi *et al.*[61]	36	29	Brachial plexus trauma	Spinal accessory nerve	Thoracoacromial artery, cephalic vein	0	11	25	119	None reported
Doi *et al.*[62]	34	23	Brachial plexus trauma	Spinal accessory nerve	Not specified	NR	NR	NR	118	None reported
Elzinga *et al.*[63]	2	20	Brachial plexus trauma	Spinal accessory nerve	Thoracoacromial artery and vein	0	0	2	NR	None reported
Hosseinian *et al.*[64]	12	25	Brachial plexus trauma	Contralateral medial pectoral nerve	Brachial artery, basilic vein	4	1	7	25	2 unsuccessful
Yang *et al.*[65]	47	26	Brachial plexus trauma	45 spinal accessory nerve 2 phrenic nerve	Brachial artery, axillary artery, or subclavian artery; comitantes vein	5	1	36	106	2 thrombosis with flap failure (immediately received second transfer)
Maldonado *et al.*[52]	39 (29 biceps attachment, 10 distal attachment)	34 biceps attachment 25 distal (FDP/FPL) attachment	Brachial plexus trauma	13 intercostal 26 spinal accessory	Thoracoacromial artery; cephalic vein	10 (biceps) 0 (FDP/FPL)	9 (biceps) 1 (FDP/FPL)	10 (biceps) 9 (FDP/FPL)	111 (biceps) 127 (FDP/FPL)	None reported
Potter *et al.*[66]	13	32	Brachial plexus trauma	Spinal accessory	Thoracocromial artery; cephalic vein	0	0	13	102	1 venous congestion
Nicoson *et al.*[67]	13	34	Brachial plexus trauma	4 spinal accessory 1 spinal accessory+ intercostal+ rectus abdominis 1 intercostal 3 intercostal + rectus abdominis 1 medial pectoral nerve 2 FCU fascicle of ulnar nerve 1 thoracodorsal	Thoracoacromial artery or brachial artery	3	4	6 (mean 4.5 MPN, 4 TD, 3.3 intercostal, 3 SAN, 3 SAN + ICN, 2 FCU)	NR	None reported
Estrella *et al.*[68]	42	29	Brachial plexus trauma	41 spinal accessory 1 intercostal nerve	Thoracoacromial artery; cephalic vein	5	9	28	107	4 flap failures 1 peroneal nerve palsy

										3 wound dehiscence 3 revision tensioning 2 skin flap necrosis 2 transient sensory disturbance at knee
El-Gammal *et al.*[69]	15	102.5 months	Obstetric brachial plexus palsy	Intercostal nerves (4,5) Phrenic nerve Spinal accessory nerve	Not specified	0	1	14	104	None reported
Chim *et al.*[70]	12	14	Brachial plexus trauma	Intercostal nerves Spinal accessory nerve	Not specified	1	3	8	79 (mean arc)	2 elbow flexion contractures 2 arterial thrombosis (stage 2, double transfer) 1 wound dehiscence
Coulet *et al.*[71]	12	26	Brachial plexus trauma	Intercostal nerves	Not specified	2	0	10	128 (partial injuries) 103 (complete injuries)	2 failures
Sochol *et al.*[72]	1	5	Arthrogryposis	Branch to pectoralis major (lateral pectoral)	Thoracoacromial artery and vein	0	0	1	140	None reported
Martins-Filho *et al.*[48]	23	33	Brachial plexus trauma	18 spinal accessory 3 intercostal nerve	18 thoracoacromial artery 3 thoracodorsal artery 1 brachial artery	5	9	9	NR	None reported
Bertelli *et al.*[51]	24	34	Brachial plexus trauma	Median nerve fascicles or ulnar nerve fascicles	Radial artery; cephalic vein	1	7	16	108	1 arterial occlusion 1 arterial wall rupture 1 epicondyle fracture (during Steindler flexorplasty) 4 hematoma
Madura *et al.*[73]	17	13	Brachial plexus trauma	Spinal accessory nerve	Thoracoacromial artery; cephalic vein	0	3	14	119	3 bowstringing
Cho *et al.*[74]	38	28	Brachial plexus trauma	18 spinal accessory nerve 20 motor fascicles of ulnar nerve	Thoracoacromial artery and vein	12	9	17	NR	2 vascular impairment of skin paddle 2 infection
Nath *et al.*[75]	24	10 obstetric 27 traumatic	13 obstetric plexus palsy 11 brachial plexus trauma	18 median nerve branch 5 radial nerve branch 1 ulnar nerve branch	Not specified	8	11	5	NR	NR
Kimura *et al.*[76]	8	31	Brachial plexus trauma	Spinal accessory or intercostal nerve	Anterior humeral circumflex artery, deep	4	0	4	NR	None reported

					brachial artery, or thoracoacromial vessels					
Potter *et al.*[66]	17	33	Brachial plexus trauma	Spinal accessory nerve	Thoracoacromial artery; cephalic vein	2	0	15	92	1 exploration for venous congestion
Yavari *et al.*[77]	63	23	Brachial plexus trauma	Contralateral medial pectoral nerve + sural graft	Brachial artery	16	26	21	NR	2 flap failures
De Rezende *et al.*[78]	21	32	Brachial plexus trauma	Ulnar nerve fascicle	Thoracoacromial artery and vein	3	5	13	86	None reported

Rectus femoris

An alternative option for free functional muscle transfer to restore elbow flexion is the use of rectus femoris. This may be useful when the gracilis muscles are unavailable for use, whether as a result of injury or after use for a different function. The rectus femoris is a fusiform muscle that generates more force than the gracilis, and may lead to stronger elbow flexion, though comparative studies are lacking[79].

An incision is created along the anterior thigh in line from the anterior inferior iliac spine to the patella. A skin paddle may be incorporated into the incision. The rectus femoris and sartorius muscles are identified below the fascia, and the sartorius is retracted medially. As mentioned above, marking sutures may be placed at fixed intervals to define the normal resting length of the muscle. The descending branch of the lateral femoral circumflex vessels and branches of the femoral nerve are identified medial to the muscle. The rectus femoris is then elevated from distal to proximal and lateral to medial with care to avoid injury to the pedicle. Distally, the muscle is divided 6cm above the patella to preserve the quadriceps tendon[79].

The recipient site is prepared as explained previously. The proximal end of the muscle is fixed to the coracoid or lateral clavicle and acromion with suture, suture anchors, or bone tunnels. As with the free latissimus and gracilis transfers, the pedicle anastomosis can be performed to an available artery in an end-to-end or end-to-side fashion. Similarly, tension is set with the elbow in extension to restore the distance between the previously placed marking sutures and the distal end of the transferred rectus is fixed to the biceps tendon. The donor nerve of choice is then sutured to the motor branch of the femoral nerve innervating the rectus femoris.

Reported outcomes are shown in Table 4. While there are fewer reported cases using a rectus femoris muscle transfer compared to latissimus or gracilis transfer, the results are promising. In the studies which reported individual distributions of motor grades, 83% achieved at least antigravity strength.

Medial gastrocnemius

The medial gastrocnemius muscle is less frequently used as a free functional muscle transfer option for restoration of elbow flexion, which may be used if other

Table 4. Reported outcomes of free rectus femoris transfer. MRC: Medical Research Council muscle grade

Reference	Number of patients	Mean age (years)	Pathology	Neurotization	Vessel anastomosis	Elbow flexion MRC < 3	MRC 3	MRC ≥ 4	Mean elbow flexion (degrees)	Complications
Chuang *et al.*[16]	1	Not specified	Brachial plexus trauma	Intercostal nerves	Not specified	0	1	0	NR	None reported
Akasaka *et al.*[80]	11	Not specified	Brachial plexus trauma	Intercostal nerves (3, 4)	Anterior circumflex humeral artery or profunda brachii artery; cephalic vein or brachial vena comitantes	3	8	0	80+ in 8 100+ in 3	2 failures, thrombosis
Wechselberger *et al.*[79]	1	22	Brachial plexus trauma	Spinal accessory nerve	Brachial artery and vein	0	0	1	110	None reported
Doi *et al.*[81]	7	25	Brachial plexus trauma	Spinal accessory nerve	Thoracoacromial artery; cephalic vein	NR	NR	NR	34	3 skin paddle necrosis
Terzis *et al.*[44]	7	NR	Brachial plexus trauma	4 contralateral C7 2 intercostals 1 cervical plexus	Not specified	Mean muscle grade reported Intercostal 2.77 Cervical plexus 2.33 cC7 3.67			NR	None reported

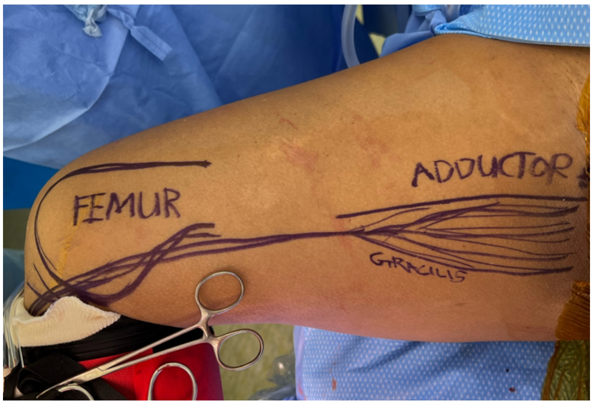

Figure 7. The relevant anatomy and planned incision for harvest of the gracilis muscle.

donors are unavailable. The technique is described by de Moraes *et al.*[34] An incision is made from 8 cm proximal to the popliteal crease to 10 cm proximal to the medial malleolus. The septum between the two heads of the gastrocnemius muscle is identified and dissected, retracting the lesser saphenous vein and sural nerve laterally. Marking sutures may be placed at a fixed distance. The medial sural artery and nerve to the medial gastrocnemius, branching from the tibial nerve, are identified between the heads of the gastrocnemius. Proximally, the medial gastrocnemius muscle is divided at the medial femoral condyle, and distally at the musculotendinous junction[34]. Transfer to the recipient site is performed as described above. De Moraes *et al.* describe functional outcomes similar to pedicled latissimus transfer, where all patients achieved at least antigravity strength [Table 5][34].

DONOR VESSELS

The choice of the donor artery and vein to supply the transferred muscle is variable and depends on

Table 5. Reported outcomes of free medial gastrocnemius transfer. MRC: Medical Research Council muscle grade

Reference	Number of patients	Mean age (years)	Pathology	Neurotization	Vessel anastomosis	Elbow flexion MRC < 3	MRC 3	MRC ≥ 4	Mean elbow flexion (degrees)	Complications
De Moraes *et al.*[34]	7	28	Brachial plexus trauma	Ulnar nerve fascicle Intercostal nerve Spinal accessory nerve	Thoracodorsal artery; thoracodorsal vein and cephalic vein	0	3	4	83	None reported

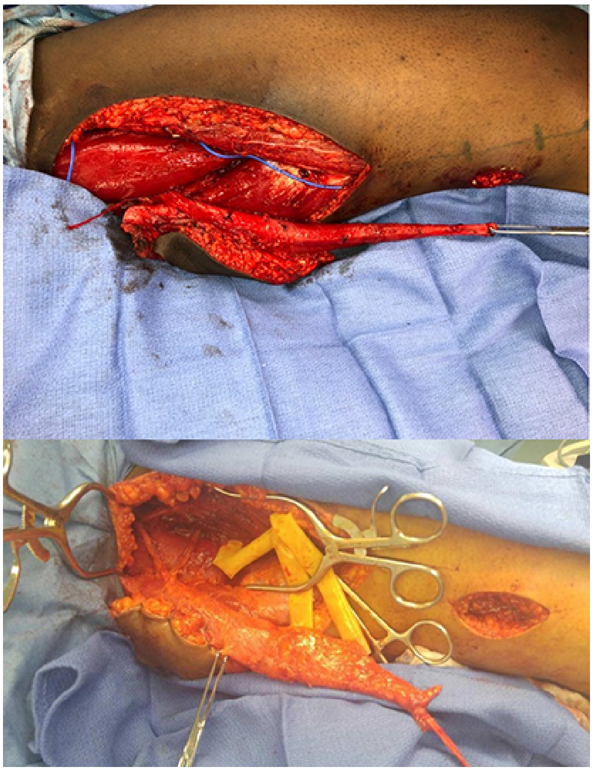

Figure 8. Harvest of the gracilis muscle for free functional muscle transfer.

individual anatomy, the length of the harvested pedicle, and the presence of pre-existing injuries. The anastomosis may be performed in an end-to-end or end-to-side fashion, depending on the chosen vessels. A meta-analysis comparing end-to-end and end-to-side anastomoses showed no significant difference in flap failure[82]. For transfers to restore elbow flexion, the thoracoacromial artery (end-to-end) or brachial artery (end-to-side) are commonly chosen vessels due to proximity and size match [Tables 1-4]. Most importantly, ischemia time and tension on the pedicle should be minimized[48].

DONOR NERVES

As described above, there are a variety of options for innervation of functional muscle transfers for brachial plexus injuries. Mahmood *et al.* evaluated axon counts in the nerve to the gracilis and found that the spinal accessory or two or three intercostals are all sufficient for transfer to the nerve to the gracilis[83]. When the musculocutaneous nerve or other intraplexal nerves are present, these should be used to innervate the transferred muscle, such as when free functional muscle transfer is used for treating anterior compartment

Figure 9. Planned incision for transfer of the gracilis muscle to the anterior arm.

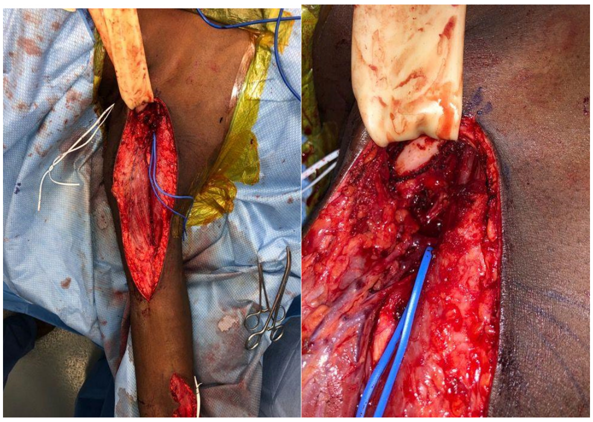

Figure 10. Dissection of the donor artery in the anterior arm for transfer of the gracilis muscle.

loss[49]. Silva *et al.* compared gracilis muscle transfers innervated by the spinal accessory nerve, intercostal nerves, median nerve fascicles, ulnar nerve fascicles, or phrenic nerves. Success rates were similar between groups, with an overall success rate of 65% achieving at least grade M3 strength[53]. Nicoson *et al.* performed gracilis transfers with spinal accessory nerves, intercostal nerves (with or without rectus abdominis nerves), medial pectoral nerves, thoracodorsal nerves, and fascicle of ulnar nerves. They found a mean recovery strength of M4.5 for medial pectoral, M4 for thoracodorsal, M3.3 for intercostal, M3 for spinal accessory, and M2 for ulnar nerve fascicles, but had limited numbers[67]. Cho *et al.* compared neurotization of gracilis transfers by spinal accessory nerves or motor fascicles of the ulnar nerve, with 83% of those with spinal

Figure 11. Dissection of the distal biceps tendon for the distal attachment of the transferred gracilis muscle.

accessory nerve transfer and 55% of those with ulnar nerve fascicles reaching M3 strength or greater, but the difference was not statistically significant[74]. Chuang *et al.* showed that transferring three intercostal nerves leads to earlier recovery of muscle strength and higher final power compared to those with two transferred intercostal nerves[49]. This group showed poorer results with the use of the spinal accessory nerve to innervate the free functional muscle transfer -- 0% achieving M4 strength (compared to 78% of those with three intercostal nerves treated). However, they note the use of a nerve graft interposition when using the spinal accessory nerve to achieve the appropriate length of the transferred nerve[49]. Kimura *et al.* also noted a higher number of patients reaching M4 strength when the nerve transfer was performed without an interpositional nerve graft[76]. Terzis and Kostopoulos prefer the use of latissimus dorsi or rectus femoris transfers in most patients because of the increased strength at recovery and inadequate muscle bulk of the gracilis[44].Similar to Chuang *et al.*, Terzis and Kostopoulos also demonstrated increased strength after latissimus dorsi neurotization with three intercostal nerves compared to two[44].

Oliver *et al.* performed a systematic review and meta-analysis to compare free functional muscle transfers (gracilis, rectus femoris, and latissimus dorsi) innervated by either intercostal or spinal accessory nerves. They found no difference in success rate or muscle strength, with nearly 65% achieving at least grade M3 strength[84]. Despite the success seen with these nerve transfers, one should consider potential risks and complications. Though the use of intercostal nerves is commonly reported, the proximity to vital structures should be noted, as there have been reported pleural tears and effusions, acute respiratory distress syndrome, seroma formation, and rib fractures[85].

POSTOPERATIVE PROTOCOL

Following functional muscle transfer, patients are monitored closely for signs of flap failure, whether the transfer is pedicled or free. A skin paddle is useful in determining if early signs of flap failure are present, and may provide more successful flap salvage in the event of arterial thrombosis or venous congestion[86]. After functional muscle transfer, rehabilitation is vital to optimizing patient outcome. Typically, patients are placed in a splint postoperatively with the elbow in flexion for 1-6 weeks, following which patients begin passive therapy exercises to avoid contracture[3]. Doi *et al.* performed a trial with patients undergoing double free gracilis muscle transfer, comparing those with 6 weeks of immobilization to those with early passive mobilization after 1 week of splinting. They showed that none of the patients in the latter group required tenolysis, compared to 32% in the immobilization group, but the final range of motion was similar[62]. Following muscle reinnervation, retraining is required to train the patient to use the new elbow flexor properly.

CONCLUSIONS

Functional muscle transfer is a viable option to restore elbow flexion in the setting of brachial plexus injury, traumatic muscle loss, oncologic treatment, poliomyelitis, or congenital absence of motor function. Options include pedicled or free functional muscle transfers. Functional muscle transfer has the potential to significantly improve upper extremity function.

DECLARATIONS

Authors' contributions

Performed literature review: Vakhshori V
Prepared manuscript: Vakhshori V, Azad A

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate
Ethical approval was not applicable, and consent to participate was obtained.

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