SCIENTIFIC ARTICLE

A Comparative Outcome Study of Hamstring Versus Tibialis Anterior and Synthetic Grafts for Deltoid to Triceps Transfers

Jennifer A. Dunn, PhD,* Khalid D. Mohammed, MD,* Gordon P. Beadel, MD,* Alastair G. Rothwell, MD,* Jeremy W. Simcock, MD†

Purpose To assess elbow extension strength and complications after deltoid-triceps transfers using hamstring tendon graft compared with tibialis anterior and synthetic tendon grafts.

Methods A retrospective review of deltoid-triceps transfers in patients with tetraplegia performed between 1983 and 2014.

Results Seventy-five people (136 arms) had surgery performed, with the majority undergoing simultaneous bilateral surgery ($n = 61$; 81%). Tibialis anterior tendon grafts were used in 68 arms, synthetic grafts in 23 arms, and hamstring tendon grafts in 45 arms. The average age at surgery was 31 years. Sixty-three arms (46%) were assessed between 12 and 24 months after surgery. Seventy percent of the group ($n = 54$) were able to extend their elbow against gravity (grade 3 of 5 or greater) following surgery. Seventy-nine percent of those with hamstring grafts achieved grade 3 of 5 or more compared with 77% with tibialis anterior and 33% with synthetic grafts. There was a statistically significant difference in postsurgery elbow extension between the tibialis anterior group and the synthetic graft group and the hamstring and the synthetic graft group but not between the tibialis anterior and the hamstring group. Complications occurred in 19 arms (14%), the majority occurring immediately after surgery and associated with the wounds. The remaining complications were with the synthetic graft group in which dehiscence of the proximal attachment occurred in 30% of the arms.

Conclusions Autologous tendon grafting is associated with achievement of antigravity elbow extension in a greater proportion of individuals than with prosthetic grafting. *(J Hand Surg Am. 2017;■(■):1.e1-e9. Copyright © 2017 by the American Society for Surgery of the Hand. All rights reserved.)*

Type of study/level of evidence Therapeutic IV.

Key words Tetraplegia, tendon transfer, elbow extension, upper limb.

Online Exclusive

*From the *Department of Orthopaedic Surgery and Musculoskeletal Medicine; the †Department of Surgery, University of Otago, Christchurch, New Zealand.*

Received for publication February 18, 2016; accepted in revised form May 15, 2017.

No benefits in any form have been received or will be received related directly or indirectly to the subject of this article.

Corresponding author: Jennifer A. Dunn, PhD, Department of Orthopaedic Surgery and Musculoskeletal Medicine, University of Otago, PO Box 4345, Christchurch 8140, New Zealand; e-mail: jennifer.dunn@otago.ac.nz.

0363-5023/17/■■-0001$36.00/0
http://dx.doi.org/10.1016/j.jhsa.2017.05.013

THE SURGICAL RESTORATION OF elbow extension in people with tetraplegia was first described by Moberg[1] using the deltoid-triceps transfer. Since that time, both posterior deltoid-triceps and biceps-triceps transfers have been used to restore active elbow extension.[2–4] In a systematic review of the literature on reconstructive operations on the upper limb in tetraplegia, Hamou and colleagues[5] identified 14 studies reporting outcomes following reconstruction of elbow extension in 201 operated arms between 1977 and 2003. Adverse events associated with elbow extension reconstructions reported in this review included: rupture or stretching of the repair (the majority), elbow contracture, local infection, inflammatory reaction, heterotrophic ossification in the triceps, hematoma, and donor site toe contracture. The adverse-event rate for these procedures was 1 complication for every 4 arms.

Provision of elbow extension stabilizes the elbow and provides greater range of movement in the horizontal plane. The ability to extend the hand in space by an additional 12 inches results in an additional 800% of space that the hand can reach, thus increasing the functional workspace of the individual.[6,7] Commonly identified goals following deltoid-triceps surgery include propelling a wheelchair and transfers.[8–10] Goals directly related to self-care and dressing, driving a vehicle, and positioning the arms when lying down have demonstrated the greatest level of satisfaction following deltoid-triceps surgery.[8]

Restoration of elbow extension after spinal cord injury (SCI) can be performed by transferring the posterior third of the deltoid muscle into the insertion of the triceps tendon via a tendon graft. A variety of tendons have been used to bridge the gap between the deltoid and the triceps, including the extensor digitorum longus, the tibialis anterior, the fascia lata, the central third of the triceps tendon, and synthetic material.[1,2,4] For those patients who require restoration of active extension of both elbows, simultaneous bilateral surgery is performed, ideally prior to hand surgery. Providing elbow extension prior to surgical restoration of the hand ensures there is an antagonist to elbow flexion that can counteract the flexion moment that is produced after a tendon transfer using the brachioradialis.[11]

Between 1983 and 2000, the tibialis anterior was used as the graft for deltoid-triceps transfer in 68 arms.[12] Rehabilitation of bilateral deltoid to triceps transfer using tibialis anterior grafts involved an initial 6-week period of bedrest with the arms immobilized in a crucifix position, followed by a further 8 weeks of gradual mobilization of elbow flexion increasing 15° each week until full flexion was reached. Patients remained inpatients for the period of their rehabilitation. This was due to the burden of care required for patients following bilateral surgery and the specialized nature of the rehabilitation. The increasing international use of synthetic grafts enabling decreased immobilization time, earlier rehabilitation,[13] and the increasing number of incomplete SCI were the reasons for changing to a synthetic graft between 2000 and 2004 in 23 arms. This decreased the postoperative bedrest time to 10 days, prior to the 8-week gradual mobilization of elbow flexion, ultimately decreasing the length of hospital stay by 4 weeks. In addition, the use of a synthetic graft enabled people with incomplete SCI to have elbow extension reconstructed without compromising their lower limb function. A number of complications and poor outcomes following use of the synthetic graft necessitated an abandonment of this surgical technique. From 2005, deltoid-triceps transfers have been performed using hamstring grafts (45 arms) because they have been proven to be a graft donor with minimal donor site morbidity in other orthopedic procedures such as anterior cruciate ligament reconstructions.[14,15] The purpose of this paper is to describe the surgical technique and rehabilitation of this procedure and to assess the outcomes in terms of elbow extension strength and complications compared with historical data on tibialis anterior and synthetic grafts.

METHODS

Patient population

All patients with tetraplegia assessed for surgery are enrolled in a secure International Upper Limb Surgery Registry, approved by a regional ethics committee.[16] Patients were included in the study if they had deltoid-triceps surgery performed between January 1, 1983, and December 31, 2014, had been followed up by the upper limb surgery team between 12 and 24 months following surgery, and had elbow extension strength formally tested and recorded. Those excluded from the study were those who had died prior to the 12- to 24-month follow-up (n = 1), those without documented presurgery muscle strength scores, and those who had been followed up at an earlier or later time (n = 38).

Surgical prerequisites

A Medical Research Council (MRC) grade 4 of 5 or 5 of 5 posterior deltoid is required for transfer.[17] However, because we routinely perform bilateral simultaneous surgery, transfers of posterior deltoid with strength less than grade 4 of 5 were performed on 3 arms (2 synthetic, 1 hamstring).

Surgical technique

Transfer using hamstring tendon grafts: In the prone patient and via a 4-cm longitudinal incision over the anteromedial tibia at the level of the tibial tubercle, the gracilis and semitendinosis tendons are identified,

FIGURE 1: Identification and mobilization of hamstring tendon grafts.

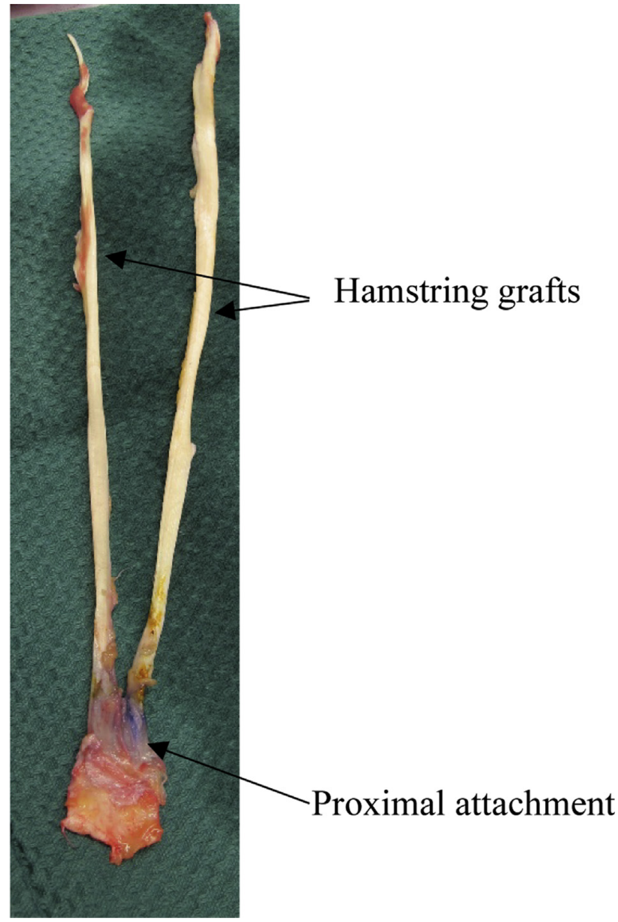

FIGURE 2: Hamstring tendon grafts.

mobilized proximally by blunt dissection, and retrieved using a slotted tendon stripper (Fig. 1).

These are then sharply dissected off the proximal tibia as a conjoined tendon insertion. The tendons are cleaned of any remaining muscle and wrapped in saline-soaked gauze (Fig, 2).

In the prone position, an oblique skin incision is performed over the posterior third of the deltoid. The deep fascia is divided and the posterior border of the deltoid muscle identified. The posterior third of the deltoid is separated from the anterior two-thirds and detached subperiosteally, preserving as much periosteum with tendon distally as possible. The location of the axillary and radial nerves is found but they are not routinely exposed. The radial nerve is normally protected by a fascial layer behind the posterior deltoid, and proximal dissection of the deltoid does not extend up as far as the axillary nerve. The conjoined hamstring tendon graft is sutured to the proximal deltoid tendon on the deep surface of the muscle with multiple interrupted 2-0 polyester sutures. Then the 2 tendons are woven individually through the distal deltoid tendon in 2 interweaves and again secured by 2-0 polyester interrupted sutures (Fig. 3).

A 6-cm oblique skin incision is made over the distal portion of the triceps tendon and a subcutaneous tunnel developed by blunt dissection between the 2 incisions. The free ends of the tendon graft are passed through the subcutaneous tunnel, woven individually into the distal triceps tendon, and secured with 2-0 polyester interrupted sutures (Fig. 4).

Tension of the tendon transfer is adjusted ensuring that, with the shoulder abducted to 90°, the elbow can be passively flexed to 60° without causing excessive tension in the graft. In addition, it is necessary to check that the arm can be safely placed at the side of the trunk with the elbow straight. The elbow is maintained in full extension while a layered closure of the subcutaneous tissue and skin is performed. Dressings and a well-padded elbow range of motion (ROM) brace, locked into full extension, are applied.

Transfer using tibialis anterior tendon graft: The surgical technique for the deltoid-triceps transfer using tibialis anterior graft has been previously described by Rothwell and Sinclair.[18]

Transfer using synthetic tendon graft: The posterior deltoid was mobilized as described using the hamstring graft. The distal incision was extended further distally over the olecranon process to the proximal ulna and a subcutaneous tunnel was made by blunt dissection between the 2 incisions. The mobilized posterior deltoid and tendon were encased in the funnel-shaped proximal end of the synthetic graft and secured by multiple interrupted 2-0 polyester sutures. The distal end of the graft was fed through the subcutaneous tunnel. A dental bur was used to make a tunnel through the proximal ulnar through which the 2 tails

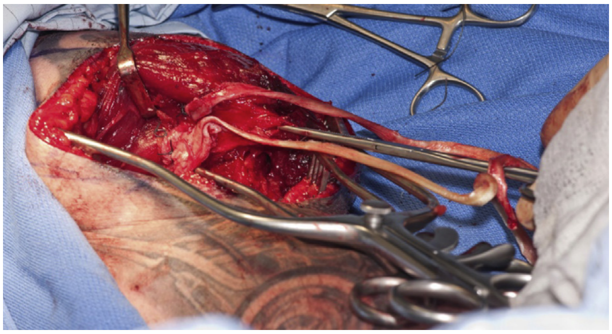

FIGURE 3: Proximal attachment of hamstring graft to posterior deltoid tendon.

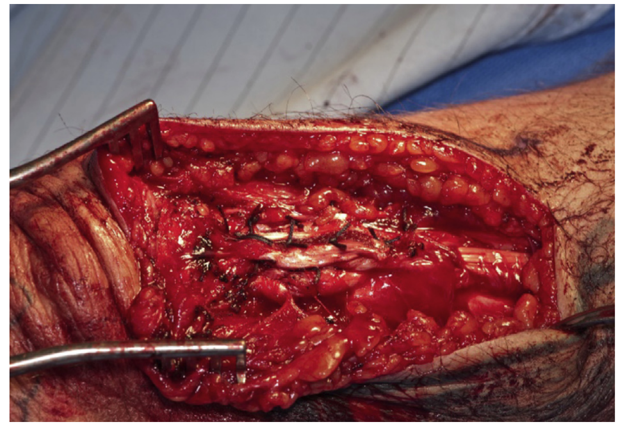

FIGURE 4: Attachment of hamstring grafts to distal triceps tendon.

of the distal portion of the synthetic graft were passed, 1 from each side. Once appropriate tension was obtained, the graft was sutured to adjacent tissues and the free ends of the tails were sutured back onto the main body of the synthetic tendon with 2-0 polyester sutures.

Postoperative regimen following hamstring graft

Following surgery, the patient remains on bedrest with the arm abducted in the crucifix position for 7 days with the ROM brace locked in full extension. The crucifix position is maintained with the use of specialized armboards that are attached to the hospital bed. Gradual adduction of the arm down to the trunk begins after 7 days, and once this is pain-free, the patient mobilizes in a power wheelchair (between 10 and 14 days after surgery). The arm must not cross the midline (owing to increased tension on the proximal weave) so careful positioning, especially in bed, to prevent this for the duration of brace use is imperative. At 14 days after surgery, elbow extension reeducation commences with the ROM brace unlocked to the degree of elbow flexion to which the patient is able to comfortably flex (usually about 60° initially) and increased up to twice weekly to allow further elbow flexion (~ 20° each subsequent week). Tendon transfer activation is commenced with gravity eliminated. Brace adjustment for more flexion is delayed if an extension lag develops. Functional activities of daily living are incorporated into therapy as elbow flexion increases allow. The brace is continued until 90° of elbow flexion is attained (~ 4 weeks following surgery) and is then worn only at night for a further 2 weeks. Antigravity muscle strengthening is commenced at 5 weeks after surgery and manual wheelchair propulsion and body weight transfers can be commenced at 6 weeks after surgery. Care must be taken to ensure that stretching/rupture of the graft does not occur owing to the patient falling onto a bent elbow during rehabilitation at this time.

Comparison of rehabilitation of deltoid-triceps transfer using hamstrings to tibialis anterior and synthetic graft

As mentioned previously, the rehabilitation protocol for the tibialis anterior tendon entailed a longer after-surgery immobilization both on bedrest (6 weeks) and then an 8-week rehabilitation period. Changing to the synthetic graft reduced the bedrest time to 10 days, which is the same as the hamstring graft, before the 8-week rehabilitation period similar to the tibialis anterior graft. Thus, the synthetic graft decreased the rehabilitation time from 14 weeks to 10 weeks. In comparison, owing to the strength of the union of the hamstring tendon graft and deltoid tendon prior to suturing, the rehabilitation period for the hamstring tendon has decreased even further to 6 weeks.

Assessment of muscle strength

Manual muscle testing was performed according to accepted standards by either the surgeon (K.D.M., G.P.B., A.G.R., or J.W.S.) or the therapist (J.A.D.), and usually together to reach consensus, with specific assessment of presurgery posterior deltoid and triceps strength and postsurgery elbow extension.[19] Assessment of posterior deltoid strength was performed as described by Leclercq et al[11] with the patient sitting in the wheelchair with the trunk stabilized by the tester or with the elbow of the opposite arm hooked around the handle of the wheelchair. The patient then abducts the arm to 90° and is then asked to extend the shoulder back against the tester's palm that is placed on the distal end of the humerus. If the patient's arm can easily be pushed out of the extended position, the strength of the posterior deltoid is grade 3. A grade 3

TABLE 1. Demographics of Whole Population by Graft Type

	Tibialis Anterior (n = 37)	Synthetic (n = 13)	Hamstring (n = 25)	Total Population (n = 75)
M:F	34:3	13:0	21:4	68:7
Average age at injury, y (SD)	22 (7)	23 (6)	24 (12)	23 (9)
Average age at surgery, y (SD)	29 (9)	34 (9)	31 (10)	31 (10)
Time of injury to surgery, y (SD)	7 (6)	10 (9)	7 (9)	7 (7)
Number of arms	68	23	45	136

of 5 was recorded if the elbow was actively extended against gravity through a full range without a lag, but without resistance. Grade 4 is given if moderate resistance is required to push the arm out of the extended position, and grade 5 if the arm does not move out the extended position with maximum resistance. This assessment of posterior deltoid strength is different from MRC criteria for testing these grades,[19] mainly owing to the difficulty and time limitations in a clinic situation to position the tetraplegic person prone on the edge of a bed to perform antigravity shoulder extension. The pragmatic approach by Leclercq et al[11] was therefore used.

For measurement of elbow extension, care was taken to prevent substitution patterns such as shoulder external rotation.

Statistical analysis

A generalized Cochran-Mantel-Haenszel test was used to determine if there was an association between graft type and MRC (treated as an ordinal variable). Then, pairwise comparisons, with *P* values corrected for multiple comparisons using Holm's method were used to determine statistical significance. The level of significance was set at *P* less than .05.

RESULTS

Patient population

A total of 75 people (136 arms) with tetraplegia had deltoid-triceps surgery performed between 1983 and 2014. Of these, 61 people (81%) had bilateral simultaneous surgery, with the remainder having reconstruction of only 1 arm. A tibalis anterior graft was used in 68 arms, a synthetic graft in 23 arms, and a hamstring graft in 45 arms. Of the 75 people who had surgery, 68 (87%) were male. Sixty-three people (84%) were classified as motor complete SCI (American Spinal Injuries Association Impairment Scale [AIS] A & B) and 5 (7%) were motor incomplete (AIS C & D). The AIS classification was unknown in 7 cases. All those who were motor incomplete had either synthetic or hamstring grafts. The SCI motor level C5 and C6 accounted for 44% (n = 33) and 45% (n = 34) of the subjects, respectively. Five percent (n = 4) were C4 motor level and the SCI level was unknown in 5% (n = 4). Demographics of subjects by graft type used in the deltoid-triceps transfers are shown in Table 1.

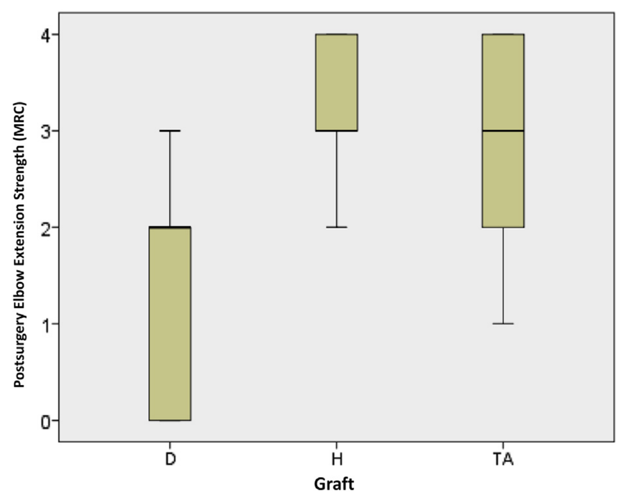

FIGURE 5: Comparision of elbow extension strength postsurgery by graft. D, synthetic; H, hamstring; TA, tibialis anterior.

For the comparison of the 3 types of tendon grafts, cases were included if they had presurgery posterior deltoid and triceps strength and 12- to 24-month postsurgery elbow extension strength recorded (Fig. 5). In total, 63 arms (n = 34 people; 46%) had these recorded; 22 tibialis anterior (11 people), 12 synthetic (7 people), and 29 hamstring (16 people). The demographics of the follow-up population are shown in Table 2.

Muscle strength

Fifty-six arms (89%) had presurgery posterior deltoid strength grade 4 of 5 or 5 of 5 (19 tibialis anterior [86%]; 10 synthetic [83%]; and 27 hamstring [(93%]) (Table 3). Ninety-two percent of all arms had a presurgery triceps strength of MRC 0 of 5 (91% tibialis anterior, 100% synthetic, 90% hamstring) (Table 4).

TABLE 2. Demographics of Follow-Up Population

	Tibialis Anterior (n = 13)	Synthetic (n = 7)	Hamstring (n = 16)	Follow-Up Population (n = 36)
M:F	11:0	7:0	13:3	31:3
Average age at injury, y (SD)	24 (5)	26 (7)	24 (10)	24 (8)
Average age at surgery, y (SD)	29 (7)	34 (8)	31 (11)	31 (9)
Time of injury to surgery, y (SD)	5 (8)	7 (7)	6 (6)	6 (7)
Mean time to follow-up, mo (SD)	15 (8)	12 (5)	10 (5)	12 (7)
Number of arms	22	12	29	63

TABLE 3. Presurgery Posterior Deltoid Strength (MRC)

MRC (Out of 5)	Tibialis Anterior (n = 22)	Synthetic (n = 12)	Hamstring (n = 29)	Total (n = 63)
2	0	1	1	2
3	3	1	1	5
4	2	3	5	10
5	17	7	22	46

TABLE 4. Presurgery Triceps Strength (MRC)

MRC (Out of 5)	Tibialis Anterior (n = 22)	Synthetic (n = 12)	Hamstring (n = 29)	Total (n = 63)
0	20	12	26	62
1	2	0	1	3
2	0	0	2	2

Following surgery, 70% of the arms (n = 44) were able to extend against gravity (MRC grade 3 of 5 or 4 of 5). When this is categorized by graft type, 77% (n = 17) of tibialis anterior grafts, 79% (n = 23) of hamstrings, and 33% (n = 4) of synthetic grafts achieved antigravity extension (Table 5). There was a statistically significant difference in postsurgery elbow extension between the tibialis anterior group and the synthetic graft group ($P < .05$) and the hamstring and the synthetic graft groups ($P < .05$) but not between the tibialis anterior and the hamstring groups.

Complications

In the whole sample (n = 136 arms), there were complications in 19 arms (14%). However, when broken down into graft type, 10 out of 23 arms using the synthetic tendon (43%) had complications compared with 6 (9%) and 3 (7%) of the tibialis anterior and hamstring grafts, respectively (Table 6). The majority of complications in both the tibialis anterior and the hamstring graft groups were related to the immediate postsurgery period with wound dehiscence or hematoma. However, for the synthetic graft group, dehiscence of the proximal attachment of the tendon prosthesis occurred in 7 (30%) of the cases and a further 2 arms (1 patient) had a persistent foreign body reaction resulting in the graft being removed 8 years following surgery. Ultrasound scans and x-rays of metal marker sutures that were routinely placed during surgery were used to diagnose proximal dehiscence of the synthetic grafts. These metal marker sutures were only used in the tibialis anterior and synthetic grafts in order to monitor tendon dehiscence during rehabilitation. The 7 patients who demonstrated dehiscence of the proximal attachment of the deltoid-triceps transfers in the synthetic group all elected not to have revision procedures.

DISCUSSION

The results of the deltoid-triceps transfer using hamstring graft in our sample are similar to our previous results using tibialis anterior tendon with

TABLE 5. Postsurgery Elbow Extension Strength by Graft Type

MRC (Out of 5)	Tibialis Anterior (n = 22)	Synthetic (n = 12)	Hamstring (n = 29)	Total (n = 63)
0	0	2	0	2
1	1	0	0	1
2	4	6	6	16
3	9	4	15	28
4	8	0	8	16

TABLE 6. Complications Following Deltoid-Triceps Transfers

Complication	Tibialis Anterior	Synthetic	Hamstring
Wound dehiscence	1	0	1
Loss radial nerve function post-op (recovered)	1	0	0
Keloid Scarring	2	0	0
Dehiscence proximal insertion of deltoid-triceps transfer	2	7	0
Amorphous calcium of soft tissue	0	0	1
Postoperative hematoma	0	0	1
Foreign body reaction to graft	0	2	0
Redundancy of tendon distally	0	1	0
Total number of arms	6	10	3

over three-quarters of all patients able to extend their arms against gravity at 12 to 24 months postsurgery and compare favorably with previously published results for both deltoid-triceps and biceps-triceps transfers.[3,5,12,20,21]

There was a statistically significant difference between our tibialis anterior and hamstring grafts results compared with our synthetic grafts in the proportion of patients achieving a functional result from elbow extension reconstruction. Initially, we changed from tibialis anterior grafts to synthetic grafts to provide posterior deltoid transfers in people with incomplete tetraplegia who required their lower limbs for ambulation and to reduce rehabilitation times. However, the poor outcomes using synthetic grafts necessitated a review of this procedure and culminated in the change to hamstring tendons. Hamstring tendons have been used for knee reconstructions for a number of decades, with minimal long-term effects on lower limb function reported.[15,22]

Use of hamstring grafts minimizes the risk of detrimental effect on lower limb function, which is especially important for incomplete SCI. Other advantages include a smaller lower limb incision that heals rapidly and the technique of securing the proximal attachment. A weak point in the fixation of the synthetic grafts was the proximal attachment to the deltoid. With the hamstring graft, the conjoined configuration of the graft used in our technique provides a good proximal fixation because the conjoined portion would have to pull through the distal deltoid to rupture. This provides confidence to accelerate the rehabilitation process and reduce the time required in ROM braces compared with other techniques.[23] Complications following hamstring graft were low (7%) compared with previously published results[5] and were related to wound problems in the immediate postsurgery period. Anecdotally, another positive feature of using hamstring grafts is that the procedure is much more readily accepted by tetraplegic persons because they are routinely used for knee reconstruction procedures in the able-bodied population with no resulting lower limb deficit. Thus, for those patients who continue to maintain hope for further recovery and/or cure from their SCI, this fact encourages them to proceed to having the surgery performed as previously discussed by Dunn et al.[24–26]

The majority of patients who received deltoid-triceps transfer using synthetic graft were unable to extend their arm against gravity and had more complications than tibialis anterior and hamstring grafts. There are a number of possible causes for these poor results including synthetic prosthesis design fault, surgical technique, and/or faulty rehabilitation protocol with inadequate protection of the transfer—despite closely following published and recommended guidelines and discussions with others using this method. One major factor possibly influencing the deltoid-triceps transfers using synthetic grafts is the bilateral simultaneous surgery that was performed. Potentially, the need to drive the power wheelchair using the operated arm may have imposed sustained stretch on the proximal attachment of the transfer, ultimately causing dehiscence. However, we are unable to ascertain in this retrospective review if this was a likely cause of failure.

The most obvious limitation to this study is the small number of cases that met the inclusion criteria for this study, mostly owing to poor historical record keeping and the loss of nearly 50% of patients to follow-up. This could be a confounding factor because those with poor results from their deltoid-triceps transfers may have been reluctant to consider further upper limb reconstructive procedures and, therefore, were the ones who were lost to follow-up.

For much of our historical data, which commenced in 1983, muscles grades were often not specifically recorded using the MRC muscle grades, but rather subjectively noted as poor, moderate, or excellent. This meant that we were unable to translate these into muscle grades. In addition, owing to the geographical location of many patients, postoperative follow-up from deltoid-triceps surgery occurred only when patients returned for further reconstructive procedures. Thus, those patients who did not return for further procedures or when these were performed either before 12 months or after 24 months, were not included in the study; however, the majority of these patients have been followed up at some point following surgery, but outside the timeframes for this study, and our reported results are indicative of what we observe clinically with these 3 graft types. Five out of 63 patients had triceps MRC grade 1 or 2 prior to surgery, 2 in the tibialis anterior group and 3 in the hamstring group. We have observed that this appears to help with initiation of contraction of elbow extension after transfer rather than contributing to their strength of elbow extension when tested at the end of range in an antigravity position.

Our outcomes using hamstring grafts have significantly improved from those using synthetic grafts and are approximately equivalent to our results for tibialis anterior grafts, despite using an accelerated rehabilitation protocol that lessens the postoperative restrictions to 4 weeks in the ROM braces and 6 weeks in total. These outcomes reinforce that the hamstring graft for deltoid-triceps transfer is an additional technique for the restoration of elbow extension, with reliable results, very low morbidity, and ready acceptance, in persons with tetraplegia, particularly those who ambulate.

REFERENCES

1. Moberg E. Surgical treatment for absent single-hand grip and elbow extension in quadriplegia. Principles and preliminary experience. *J Bone Joint Surg Am*. 1975;57(2):196–206.
2. Dunkerley AL, Ashburn A, Stack EL. Deltoid triceps transfer and functional independence of people with tetraplegia. *Spinal Cord*. 2000;38(7):435–441.
3. Kozin SH, D'Addesi L, Chafetz RS, Ashworth S, Mulcahey MJ. Biceps-to-triceps transfer for elbow extension in persons with tetraplegia. *J Hand Surg Am*. 2010;35(6):968–975.
4. McDowell CL, House JH. Tetraplegia. In: Green DP, Hotchkiss RN, Pederson WC, eds. *Green's Operative Hand Surgery*. 4th ed. Philadelphia: Churchill Livingstone; 1999.
5. Hamou C, Shah NR, DiPonio L, Curtin CM. Pinch and elbow extension restoration in people with tetraplegia: a systematic review of the literature. *J Hand Surg Am*. 2009;34(4):692–699.
6. Hentz VR, Leclercq C. *Surgical rehabilitation of the upper limb in tetraplegia*. New York: WB Saunders; 2002.
7. Robinson M, Barton G, Lees A, Sett P. Analysis of tetraplegic reaching in their 3D workspace following posterior deltoid-triceps tendon transfer. *Spinal Cord*. 2010;48(8):619–627.
8. Wangdell J, Fridén J. Activity gains after reconstruction of elbow extension in patients with tetraplegia. *J Hand Surg Am*. 2012;37(5):1003–1010.
9. Wangdell J, Friden J. Satisfaction and performance in patient selected goals after grip reconstruction in tetraplegia. *J Hand Surg Eur Vol*. 2010;35(7):563–568.
10. Lamberg A-S, Fridén J. Changes in skills required for using a manual wheelchair after reconstructive hand surgery in tetraplegia. *J Rehabil Med*. 2011;43(8):714–719.
11. Leclercq C, Hentz VR, Kozin SH, Mulcahey MJ. Reconstruction of elbow extension. *Hand Clin*. 2008;24(2):185–201.
12. Mohammed KD, Rothwell AG, Sinclair SW, Willems SM, Bean AR. Upper limb surgery in tetraplegia. *J Bone Joint Surg Br*. 1992;74(6):873–879.
13. Hentz VR, House J, McDowell C, Moberg E. Rehabilitation and surgical reconstruction of the upper limb in tetraplegia: an update. *J Hand Surg Am*. 1992;17(5):964–967.
14. Pagnani MJ, Warner JJ, O'Brien SJ, Warren RF. Anatomic considerations in harvesting the semitendinosus and gracilis tendons and a technique of harvest. *Am J Sports Med*. 1993;21(4):565–571.
15. Sgaglione NA, Warren RF, Wickiewicz TL, Gold DA, Panariello RA. Primary repair with semitendinosus tendon augmentation of acute anterior cruciate ligament injuries. *Am J Sports Med*. 1990;18(1):64–73.
16. Sinnott KA, Dunn JA, Rothwell AG, Hall A, Post MW. The development of the NZ based International Upper Limb Surgery Registry. *Spinal Cord*. 2014;52(8):611–615.
17. McDowell CL, Moberg E, House JH. The Second International Conference on Surgical Rehabilitation of the Upper Limb in Tetraplegia (Quadriplegia). *J Hand Surg Am*. 1986;11(4):604–608.
18. Rothwell AG, Sinclair SW. Upper limb tendon surgery for tetraplagia. *Oper Orthop Traumatol*. 1997;9(3):199–212.
19. Kendall FP, McCreary EK, Kendall HO. *Muscles, Testing and Function: Testing and Function*. Philadelphia: Lippincott Williams & Wilkins; 1983.
20. Connolly SJ, Aubut JL, Teasell R, Jarus T, SCIRE Research Team. Enhancing upper extremity function with reconstructive surgery in persons with tetraplegia: a review of the literature. *Topics Spinal Cord Injury Rehabil*. 2007;13(1):58–80.

21. Mulcahey MJ, Lutz C, Kozin SH, Betz RR. Prospective evaluation of biceps to triceps and deltoid to triceps for elbow extension in tetraplegia. *J Hand Surg Am*. 2003;28(6):964−971.
22. Lipscomb AB, Johnston RK, Snyder RB, Warburton MJ, Gilbert PP. Evaluation of hamstring strength following use of semitendinosus and gracilis tendons to reconstruct the anterior cruciate ligament. *Am J Sports Med*. 1982;10(6):340−342.
23. Koch-Borner S, Dunn JA, Fridén J, Wangdell J. Rehabilitation after posterior deltoid to triceps transfer in tetraplegia. *Arch Phys Med Rehabil*. 2016;97(6 Suppl):S126−S135.
24. Dunn J, Hay-Smith E, Whitehead L, Keeling S. Issues influencing the decision to have upper limb surgery for people with tetraplegia. *Spinal Cord*. 2012;50(11):844−847.
25. Dunn JA, Hay-Smith EJC, Whitehead LC, Keeling S. Liminality and decision making for upper limb surgery in tetraplegia: a grounded theory. *Disabil Rehabil*. 2013;35(15):1293−1301.
26. Dunn JA, Hay-Smith EJ, Keeling S, Sinnott KA. Decision-making about upper limb tendon transfer surgery by people with tetraplegia for more than 10 years. *Arch Phys Med Rehabil*. 2016;97(6 Suppl): S88−S96.