Femoral nerve palsy results in significant impairment of lower extremity function due to the loss of quadriceps muscle function. Etiologies are varied with the leading cause being iatrogenic, often related to orthopedic procedures around the hip joint or retroperitoneal procedures. In our practice, palsy following hip surgery is most common. Mechanisms of injury may include traction or compression from retraction, direct crush or transection injury, compression from bleeding or hematoma, and thermal damage or entrapment from bone cement. Significant recovery, if forthcoming, will usually occur within 6–7 months but is less likely in complete palsies.

Surgical treatment is dictated by the injury level. The results of femoral nerve repair and nerve grafting at the thigh level, if appropriate, are good. However, in many cases, including after hip surgery, the proximal nerve outside the zone of injury is inaccessible or unavailable, and nerve repair or grafting is inappropriate. These cases led to the introduction of nerve transfers when presenting within 1 year of injury. After 1 year, the target muscles will no longer be responsive to reinnervation because of atrophy and degeneration of the neuromuscular junction and the muscle itself. Nerve transfers have demonstrated encouraging results in managing brachial plexus and up-
New Techniques and Donors in Nerve Transfers for Femoral Nerve Palsy

We have previously reported on nerve transfers utilizing two branches from the anterior branch of the obturator nerve (gracilis and adductor longus) as donors for nerve transfer to reinnervate the rectus femoris and vastus medialis muscles with good outcomes. Our technique has since evolved to increase the number of muscles reinnervated. We now perform a more proximal dissection of the obturator nerve in order to utilize the branch to the adductor brevis muscle as well as to optimize the number of axons available for transfer. With the recent recognition of sartorius nerve branches as an additional donor in many cases of femoral nerve palsy, we are now able to utilize more donor axons and potentially reinnervate all of the quadriceps muscles if needed.

Supercharged End-to-Side Nerve Transfers in Femoral Nerve Palsy

The “supercharged end-to-side” (SETS) transfer augments recovery in incomplete nerve injuries in which an end-to-end (ETE) transfer may downgrade recovered or remaining function. This technique transfers functioning donor axons through an epineurial and/or perineurial window to the side of an incompletely injured recipient nerve.

The purpose of this article is to provide an update on our surgical techniques and approach to nerve transfers in both partial and total femoral nerve palsies and expand our case series to demonstrate the functional outcomes achieved with nerve transfers from the anterior branch of the obturator nerve and/or sartorius nerve branches.

Methods

After obtaining institutional review board approval, we conducted a retrospective review of patients with partial or total femoral nerve palsy that had been treated with femoral nerve decompression and ETE and/or SETS nerve transfers at the Washington University School of Medicine in 2008–2019. Partial femoral nerve palsy was defined as preoperative Medical Research Council (MRC) grade ≥ 1, and total femoral nerve palsy was defined as preoperative MRC grade 0. Nerve transfers included as donors the anterior branch of the obturator nerve, the sartorius branches, or both. Primary outcomes were active knee extension by MRC grades and visual analog scale (VAS) scores for pain. Outcomes were assessed based on the type of nerve transfer (ETE vs SETS), based on partial versus total femoral nerve palsy, and as an overall cohort.

Descriptive statistics were calculated for continuous (mean ± standard deviation) and categorical (frequency) variables. Outcomes data were visually inspected using histograms to determine normality. Comparisons between preoperative and postoperative VAS pain scores were made using the paired Wilcoxon signed-rank test. Significance was set a priori at p < 0.05, and SPSS version 26 (IBM Corp.) was used for all analyses.

Treatment Algorithm

Our treatment algorithm involves a period of monitoring for spontaneous recovery. This includes serial physical examination and electrodiagnostic testing (EDX) starting at 3 months after injury. If there is delayed or no evidence of spontaneous recovery (e.g., motor unit action potentials [MUAPs]) on EDX, then we offer surgical intervention by 6 months. The presence of fibrillations (fibs) and/or positive sharp waves (PSWs) in the quadriceps muscles on electromyography (EMG) provides evidence that the muscle is not terminally denervated and that there are unoccupied motor endplates that can be reinnervated. The type of nerve transfer (ETE vs SETS) depends on the findings on preoperative EMG and intraoperative nerve stimulation. The presence of MUAPs on EMG suggests spontaneous recovery and is confirmed with intraoperative nerve stimulation. In these cases, an SETS transfer is performed to preserve and augment the regenerating native motor nerve. If MUAPs and intraoperative nerve stimulation are absent, then an ETE transfer is performed.

Surgical Technique

A longitudinal incision is made in the proximal thigh beginning just below the groin crease about two-thirds of the way between the anterior superior iliac spine and the pubic tubercle, just lateral to the palpable femoral vessels. Right: Incision for exposure of the obturator nerve. A second incision is made in an oblique fashion just below the groin crease, starting slightly medial to the incision made for the femoral nerve exposure. This incision extends medially past the adductor longus tendon. Figure is available in color online only.
the superficial motor branches of the femoral nerve innervating the sartorius muscle (Fig. 2 left). These should be preserved, as they are often spared in femoral nerve injuries and can be used as donors for nerve transfer if functioning. Following identification of the sartorius branches, the medial border of the sartorius is dissected. Quadriceps branches lie just below the medial border of the sartorius, under a third, often thickened layer of fascia—the femoral sheath.

Topography of the quadriceps branches is well described in our previous publication. The medial-most branch running with the vessels is the saphenous portion of the femoral nerve. This is followed (from medial to lateral) by branches to the vastus medialis, vastus intermedius, vastus lateralis, and rectus femoris muscles. Branches are stimulated to assess function and determine the most appropriate nerve transfer(s). The quadriceps branches are neurolysed as much as possible proximally to maximize length for transposition and reduce either the likelihood of needing a nerve graft or the length of graft required.

Adequate neurolysis of recipient quadriceps branches is more important in the case of obturator to femoral nerve transfers, as opposed to sartorius to femoral nerve transfers, as the obturator nerve is further away. When performing an SETS transfer, the sartorius motor branches are preferred donors if available because of their proximity, as using the obturator nerve may require the use of a nerve graft.

If the obturator nerve is to be used for nerve transfer, a second oblique incision is made just below the medial groin crease, extending medially past the adductor longus tendon and through the muscle fascia (Fig. 1 right). The adductor longus muscle is identified, and an interval is bluntly dissected between the adductor longus and the pectineus muscles. In this interval, lying on the surface of the adductor brevis muscle, are the three motor branches of the anterior obturator nerve to innervate the adductor longus, adductor brevis, and gracilis muscles (Fig. 2 right). These branches are confirmed by electrical stimulation. They are then mobilized and divided as distally as possible at their point of entry into muscle to maximize length. A tunnel is made connecting the anterior and medial thigh incisions. The posterior branch of the obturator nerve is preserved to maintain adductor magnus function and active thigh adduction. In an ETE transfer, the recipient branches of the femoral nerve are then transected as proximally as possible and transposed medially toward the obturator branches. The femoral nerve branches that are recipients for sartorius nerve transfers do not require transposition because of the proximity of the sartorius branches (Fig. 3A and B). For SETS transfers, the obturator branches are transposed laterally to the femoral motor branches (Fig. 3C). See Fig. 4 for a clinical example of a combination of ETE and SETS transfers. The leg is taken through a full range of motion to ensure tension-free coaptation. Coaptations are performed using a microscope and 9-0 nylon sutures.

Results

Fourteen patients with femoral nerve palsy were identified. Six patients (42.9%) were male, and average age at the time of surgery was 50.9 years (range 14–69 years). Average interval from injury to surgery was 8.5 months (range 2.6–19.2 months) with an average follow-up of 26.0 months (range 10.1–60.5 months). Except for 3, all patients underwent surgery within 5–11 months. The patient who had surgery at 2.6 months after injury was known to have undergone nerve resection, so no period of observation was necessary. The other two patients had surgery after 15.8 and 19.2 months because of late referral, but we proceeded with nerve transfers because both demonstrated positive fibs/PSWs on EMG, which indicate the potential for muscle reinnervation. The etiology of femoral nerve palsy was most often iatrogenic (8/14 [57.1%]), followed by trauma (3/14 [21.4%]), iliopsoas hematoma or compartment syndrome (2/14 [14.3%]), and idiopathic (1/14 [7.1%]).

Five patients had a preoperative MRC of 0, reflecting...
total femoral nerve palsy (Table 1). Three of them (60%) were treated with ETE nerve transfers and 2 (40%) with a combination of ETE+SETS transfers. Three (60%) attained postoperative MRC grade 4, and 2 patients (40%) had postoperative MRC grade 4+. Nine patients (9/14 [64.3%]) had a preoperative MRC grade ≥ 1, reflecting a partial femoral nerve palsy. Six (6/9 [66.7%]) were treated with SETS transfers and 2 (22.2%) with ETE+SETS transfers. One patient (11.1%) in this cohort was treated with ETE transfers, as intraoperative stimulation was absent. Of the 9 patients with partial femoral nerve palsy, 4 (44.4%) obtained postoperative MRC grade 4 and 5 pa-

![FIG. 3. A: Anatomy of femoral and obturator nerve motor branches. Anterior obturator branches (adductor brevis, adductor longus, gracilis) are located beneath pectineus and adductor longus muscles. B: Sample ETE transfers of sartorius to vastus lateralis, adductor longus to rectus femoris, and gracilis to vastus medialis motor branches. C: Sample SETS transfers of sartorius to vastus lateralis, adductor longus to rectus femoris, and gracilis to vastus medialis motor branches. AB = adductor brevis; AL = adductor longus; GR = gracilis; PE = pectineus; RF = rectus femoris; SA = sartorius; VI = vastus intermedius; VL = vastus lateralis; VM = vastus medialis. Figure is available in color online only.](image)

![FIG. 4. An example of combined anterior obturator to vastus medialis and vastus lateralis ETE and anterior obturator to rectus femoris and vastus intermedius SETS nerve transfers. Figure is available in color online only.](image)
### TABLE 1. Summary of clinical cases separated by degree of femoral nerve palsy: complete versus partial

<table>
<thead>
<tr>
<th>Age at Injury (yrs)</th>
<th>Sex</th>
<th>Etiology</th>
<th>Int, Injury to Op (mos)</th>
<th>Int, Op to FU (mos)</th>
<th>Op*</th>
<th>Preop Knee Extension (MRC)</th>
<th>Preop VAS Pain Score</th>
<th>Preop EMG</th>
<th>Intraop Stimulation Response</th>
<th>Postop Knee Extension (MRC)</th>
<th>Postop VAS Pain Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>31</td>
<td>F</td>
<td>Retroperitoneal schwannoma</td>
<td>2.6</td>
<td>60.5</td>
<td>Rt ant obturator to VM, RF ETE</td>
<td>0</td>
<td>8</td>
<td>NA</td>
<td>NA</td>
<td>RF, VM: none; VL: weak</td>
<td>4+</td>
</tr>
<tr>
<td>39</td>
<td>M</td>
<td>Skydiving accident</td>
<td>7.5</td>
<td>36.4</td>
<td>Lt tensor fascia lata to VM ETE; ant obturator to RF ETE</td>
<td>0</td>
<td>3</td>
<td>RF, VM, VI, VL: 3–4+ fibs &amp; PSWs, no MUAPs</td>
<td>RF, VM: none; VL: weak</td>
<td>4+</td>
<td>3</td>
</tr>
<tr>
<td>58</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>9.1</td>
<td>52.7</td>
<td>Lt sartorius to RF ETE; ant obturator to VM ETE w/ 4-cm graft</td>
<td>0</td>
<td>9</td>
<td>RF, VM, VI: 2+ fibs &amp; PSWs, no MUAPs</td>
<td>RF, VM, VI, VL: none</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>54</td>
<td>M</td>
<td>Idiopathic</td>
<td>5.1</td>
<td>23.7</td>
<td>Lt sartorius to VL (×2) SETS; gracilis to VM ETE; gracilis to VM SETS</td>
<td>0</td>
<td>6</td>
<td>RF: 3+ fibs &amp; PSWs, single MUAP; VM: 1+ fibs &amp; PSWs, no MUAPs; VI, VL: 3+ fibs &amp; PSWs, no MUAPs</td>
<td>RF: strong; VM, VL: none</td>
<td>4+</td>
<td>2</td>
</tr>
<tr>
<td>62</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>6.7</td>
<td>15.1</td>
<td>Rt adductor brevis to VM, adductor longus to VL ETE; gracilis to RF, VI SETS</td>
<td>0</td>
<td>1</td>
<td>RF: 2+ fibs &amp; PSWs, single MUAP; VM, VL: 2+ fibs &amp; PSWs, no MUAPs</td>
<td>RF, VI: weak; VM, VL: none; sartorius: none</td>
<td>4</td>
<td>1</td>
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<td>56</td>
<td>M</td>
<td>Pelvic tumor resection</td>
<td>19.2</td>
<td>24.3</td>
<td>Rt adductor brevis to VM, gracilis to VI ETE; sartorius to RF, VL (×2) SETS</td>
<td>1</td>
<td>8</td>
<td>VM, VL: 1+ fibs &amp; PSWs, severely reduced MUAPs</td>
<td>RF: moderate; VM, VI, VL: weak</td>
<td>4</td>
<td>6</td>
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<tr>
<td>48</td>
<td>M</td>
<td>Iliopsoas compartment syndrome</td>
<td>6.2</td>
<td>24.6</td>
<td>Lt sartorius to VL (×2) SETS; obturator to VM, VI SETS</td>
<td>2</td>
<td>3</td>
<td>RF: 2+ fibs &amp; PSWs, moderately reduced MUAPs; VM, VL: 3+ fibs &amp; PSWs, no MUAPs</td>
<td>RF: strong; VM, VI, VL: weak</td>
<td>4+</td>
<td>1</td>
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<tr>
<td>14</td>
<td>F</td>
<td>Gunshot wound</td>
<td>6.0</td>
<td>22.0</td>
<td>Lt sartorius to VM, VL, RF SETS</td>
<td>2</td>
<td>4</td>
<td>RF, VM, VL: 2+ fibs &amp; PSWs, moderately reduced MUAPs</td>
<td>RF, VM, VI, VL: weak; obturator: none</td>
<td>4+</td>
<td>0</td>
</tr>
<tr>
<td>59</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>8.4</td>
<td>24.0</td>
<td>Lt sartorius to VI, RF ETE; obturator to VM ETE</td>
<td>2</td>
<td>3</td>
<td>VM: 3+ fibs &amp; PSWs, severely reduced MUAPs; VL: 2+ fibs &amp; PSWs, moderately reduced MUAPs</td>
<td>RF, VL: twitch only; VM, VI: none</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>67</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>5.6</td>
<td>17.5</td>
<td>Lt gracilis to VM (×3) SETS; adductor longus to VI ETE w/ 2.5-cm graft</td>
<td>2</td>
<td>5</td>
<td>VM: 3+ fibs &amp; PSWs, severely reduced MUAPs; VL: 2+ fibs &amp; PSWs, moderately reduced MUAPs</td>
<td>RF, VM, VI, VL: weak</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>65</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>9.1</td>
<td>11.1</td>
<td>Lt sartorius to VL SETS; gracilis to VM, RF SETS</td>
<td>2</td>
<td>2</td>
<td>VM, VL: 2+ fibs &amp; PSWs, no MUAPs</td>
<td>RF, VM, VI, VL: weak</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>65</td>
<td>F</td>
<td>Radiofrequency ablation</td>
<td>7.0</td>
<td>10.1</td>
<td>Lt sartorius to VL (×2), RF SETS; obturator to VM, VI, RF SETS</td>
<td>2</td>
<td>8</td>
<td>RF, VM, VL: 2+ fibs &amp; PSWs, severely reduced MUAPs</td>
<td>RF, VM, VI, VL: weak</td>
<td>4+</td>
<td>5</td>
</tr>
</tbody>
</table>

CONTINUED ON PAGE 861 »
patients (55.6%) attained MRC grade 4+. None of these differences between groups was statistically significant.

Preoperative EMG was completed in all but 1 patient and demonstrated fbs/PSWs in the quadriceps muscles. The one exception was known to have undergone complete nerve resection of a retroperitoneal schwannoma; therefore, no workup was needed. Six patients (42.9%) had either a single or no MUAPs present in the quadriceps and 7 (50%) had MUAPs present in their preoperative EMG. All patients with preoperative MRC grade 0 had no MUAPs, although 2 had a single MUAP in one of the muscles. Patients with preoperative MRC grade ≥1 had moderately to severely reduced MUAPs in the muscles tested. Intraoperatively, quadriceps recipient nerves were noted to have either a weak or absent response. An absent response or a very weak response close to 1 year after injury was an indication for ETE transfer. Any greater response was an indication for SETS transfer. The response of each quadriceps muscle was assessed independently, and findings were usually mixed.

All 14 patients underwent femoral nerve decompression. Most of them underwent a combination of sartorius and obturator nerve transfers (8/14 [57.1%]). Only obturator nerve transfers were performed in 4 patients (28.6%), and only sartorius nerve transfers were performed in 2 (14.3%). An average of 3.3 transfers (range 1–6) were performed in each patient. The median preoperative knee extension in the cohort was MRC grade 2 (range 0–3). Postoperatively, all patients in the cohort obtained MRC grade 4 or greater and subjectively noted improved strength and muscle bulk and more natural gait (Videos 1 and 2).

VIDEO 1. Clip demonstrating postoperative knee extension of a patient who underwent left femoral nerve decompression and sartorius to vastus intermedius and rectus femoris ETE nerve transfers, as well as anterior obturator to vastus medialis ETE nerve transfers. Note full active extension against gravity and near-normal muscle bulk compared to the contralateral lower extremity. Copyright Thomas H. Tung. Published with permission. Click here to view.

VIDEO 2. Clip of same patient featured in Video 1, demonstrating near-normal gait without signs of a limp or imbalance. Copyright Thomas H. Tung. Published with permission. Click here to view.

Pain was typically in the saphenous distribution along the medial aspect of the thigh with burning and paresthesias. The average preoperative pain score was 5.2 (range 1–9). The average postoperative pain score was 2.3 (range 0–6), a statistically significant improvement (p = 0.001).

When grouped by the type of nerve transfer performed, SETS transfers were performed in 6 patients (42.9%), ETE transfers in 4 patients (28.6%), and a combination of SETS and ETE transfers in 4 patients (28.6%; Table 2). Mean preoperative MRC grades were 0.50 (0–2) in the ETE group, 0.75 (0–2) in the ETE+SETS group, and 2.33 (2–3) in the SETS group. All patients in each of these groups obtained a postoperative MRC grade of at least 4. One patient in each of the ETE (1/4 [25%]) and ETE+SETS (1/4 [25%]) groups had a postoperative MRC grade of +4. All patients in the SETS group had postoperative MRC grade 4+.

### Illustrative Cases

Many patients present with a mixed picture of partial recovery in some muscles and none in others, and EMG

<table>
<thead>
<tr>
<th>Age at Injury (yrs)</th>
<th>Sex</th>
<th>Etiology</th>
<th>Preop MRC grade ≥1 (continued)</th>
<th>Postop Knee Extension (MRC)</th>
<th>Postop VAS Pain Score</th>
<th>Postop EMG</th>
<th>Intraop Stimulation Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>26</td>
<td>M</td>
<td>Gunshot wound</td>
<td>10.8</td>
<td>15.8</td>
<td>0.8</td>
<td>10.8</td>
<td>RF, VL: no fbs &amp; PSWs, mildly reduced MUAPs; VM: 3+ fbs &amp; PSWs, mildly reduced MUAPs</td>
</tr>
</tbody>
</table>

* ant = anterior; FU = follow-up; Int = interval; NA = not applicable; RF = rectus femoris; VM = vastus medialis.
<table>
<thead>
<tr>
<th>Age at Injury (yrs)</th>
<th>Sex</th>
<th>Etiology</th>
<th>Int, Injury to Op (mos)</th>
<th>Int, Op to FU (mos)</th>
<th>Op*</th>
<th>Preop Knee Extension (MRC)</th>
<th>Preop VAS Pain Score</th>
<th>Preop EMG</th>
<th>Intraop Stimulation Response</th>
<th>Op Extension (MRC)</th>
<th>Op VAS Pain Score</th>
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<tr>
<td><strong>ETE only</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>31 F</td>
<td>F</td>
<td>Retroperitoneal schwannoma</td>
<td>2.6</td>
<td>60.5</td>
<td>Rt ant obturator to VM, RF ETE</td>
<td>0</td>
<td>8</td>
<td>NA</td>
<td>RF, VM, VI, VL: 3–4+ fibs &amp; PSWs, no MUAPs</td>
<td>NA</td>
<td>4</td>
</tr>
<tr>
<td>39 M</td>
<td>M</td>
<td>Skydiving accident</td>
<td>7.5</td>
<td>36.4</td>
<td>Lt tensor fascia lata to VM ETE; ant obturator to RF ETE</td>
<td>0</td>
<td>3</td>
<td>RF, VM, VI, VL: none; RF: weak</td>
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<td>3</td>
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<tr>
<td>58 F</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>9.1</td>
<td>52.7</td>
<td>Lt sartorius to RF ETE; ant obturator to VM ETE w/ 4-cm graft</td>
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<td>9</td>
<td>RF, VM, VI, VL: none</td>
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<td>F</td>
<td>Total hip arthroplasty</td>
<td>8.4</td>
<td>24.0</td>
<td>Lt sartorius to VI, RF ETE; obturator to VM ETE</td>
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<td>3</td>
<td>RF, VM, VI, VL: none</td>
<td>RF, VL: twitch only; VM, VI: none</td>
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<td>48 M</td>
<td>M</td>
<td>Iliopsoas compartment syndrome</td>
<td>6.2</td>
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<td>Lt sartorius to VL (×2) SETS; obturator to VM, VI SETS</td>
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<td>3</td>
<td>RF: 2+ fibs &amp; PSWs, moderately reduced MUAPs; VM, VI: 3+ fibs &amp; PSWs, no MUAPs</td>
<td>RF, strong; VM, VI, VL: weak</td>
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<td>Gunshot wound</td>
<td>6.0</td>
<td>22.0</td>
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<td>2</td>
<td>4</td>
<td>RF, VM, VI, VL: none; RF: weak</td>
<td>RF, VM, VI, VL: weak; obturator: none</td>
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<td>65 F</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>9.1</td>
<td>11.1</td>
<td>Lt sartorius to VL SETS; gracilis to VM, RF SETS</td>
<td>2</td>
<td>2</td>
<td>VM, VL: 2+ fibs &amp; PSWs, no MUAPs</td>
<td>RF, VM, VI, VL: weak</td>
<td>4</td>
<td>0</td>
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<tr>
<td>65 F</td>
<td>F</td>
<td>Radiofrequency ablation</td>
<td>7.0</td>
<td>10.1</td>
<td>Rt sartorius to VL (×2), RF SETS; obturator to VM, VI, RF SETS</td>
<td>2</td>
<td>8</td>
<td>RF, VM, VI, VL: weak</td>
<td>RF, RF, VI, VL: strong; VM, VL: weak</td>
<td>4</td>
<td>5</td>
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<tr>
<td>26 M</td>
<td>M</td>
<td>Gunshot wound</td>
<td>15.8</td>
<td>30.3</td>
<td>Rt sartorius to VM SETS</td>
<td>3</td>
<td>6</td>
<td>RF: no fibs &amp; PSWs, mildly reduced MUAPs; VM, VL: 2+ fibs &amp; PSWs, mildly reduced MUAPs</td>
<td>RF, RF, VL, VI: strong; VM: weak</td>
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<td>3</td>
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<td>69 M</td>
<td>M</td>
<td>Iliopsoas hematoma</td>
<td>10.8</td>
<td>11.7</td>
<td>Bilat sartorius to VI SETS; obturator to VM SETS</td>
<td>3 (bilat)</td>
<td>7</td>
<td>Bilat VM: 3+ fibs &amp; PSWs, severely reduced MUAPs</td>
<td>RF, VL: weak; VM, VI: twitch only</td>
<td>4 (bilat)</td>
<td>0</td>
</tr>
<tr>
<td><strong>ETE+SETS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>54 M</td>
<td>M</td>
<td>Idiopathic</td>
<td>5.1</td>
<td>23.7</td>
<td>Lt sartorius to VL (×2) SETS; gracilis to VM ETE; gracilis to VM SETS</td>
<td>0</td>
<td>6</td>
<td>RF: 3+ fibs &amp; PSWs, single MUAP; VM: 3+ fibs &amp; PSWs, no MUAPs</td>
<td>RF: strong; VM, VI: none</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>62 F</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>6.7</td>
<td>15.1</td>
<td>Rt adductor brevis to VM, adductor longus to VL ETE; gracilis to RF, VI SETS</td>
<td>0</td>
<td>1</td>
<td>RF: 2+ fibs &amp; PSWs, single MUAP; VM, VI: 2+ fibs &amp; PSWs, no MUAPs</td>
<td>RF: weak; VM, VI: none; sartorius: none</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>56 M</td>
<td>M</td>
<td>Pelvic tumor resection</td>
<td>19.2</td>
<td>24.3</td>
<td>Rt adductor brevis to VM, gracilis to VI ETE; sartorius to RF, VL (×2) SETS</td>
<td>1</td>
<td>8</td>
<td>VM, VL: 1+ fibs &amp; PSWs, severely reduced MUAPs</td>
<td>RF: moderate; VM, VI, VL: weak</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>67 F</td>
<td>F</td>
<td>Total hip arthroplasty</td>
<td>5.6</td>
<td>17.5</td>
<td>Lt gracilis to VM (×3) SETS; adductor longus to VI ETE w/ 2.5-cm graft</td>
<td>2</td>
<td>5</td>
<td>VM: 3+ fibs &amp; PSWs, severely reduced MUAPs; VL: 2+ fibs &amp; PSWs, moderately reduced MUAPs</td>
<td>RF, VM, VI, VL: weak</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

* All patients had femoral nerve decompression.
findings are not always consistent with intraoperative stimulation, which confounds the decision-making process. In such cases, we rely more on response to intraoperative stimulation. A couple of illustrative cases demonstrate the difficulty in classifying such patients.

A 60-year-old woman underwent left hip replacement and awakened from surgery with sciatic nerve weakness and a complete femoral nerve palsy. After several months, the sciatic nerve recovered and she noticed a little bit of recovery in her quadriceps muscles. She was able to initiate a little bit of knee extension, but since that time, there had been no further improvement. She was referred to us after 7.5 months, and on physical examination, a little bit of muscle contraction was appreciated laterally, with initiation of knee extension of only about 5°–10°. An EMG study at that time demonstrated 1–2+ fibs/PSWs in all muscles with no MUAPs. She underwent exploration 8 months after her hip surgery, and intraoperative stimulation demonstrated good contraction in her vastus lateralis muscle, a flicker of contraction in her rectus femoris muscle, and none in any other muscles. We left the vastus lateralis muscle alone, but because there was minimal function in her rectus femoris muscle, it was already 8 months after denervation, and her improvement had stalled for the last 4 months, we decided to proceed with ETE transfer. The anterior obturator and sartorius branches were transferred ETE to reinnervate her vastus medialis, intermedius, and rectus femoris muscles. After almost 2 years, she recovered MRC grade 4/5 knee extension and is able to extend her knee fully and walk short distances without a cane.

A 54-year-old gentleman developed complete femoral nerve palsy of unknown etiology the day after running upstairs. He was followed up for 5 months with no improvement until 2 weeks before his last preoperative appointment, when he developed some weak knee extension. He had significant atrophy of his quadriceps muscles except the rectus femoris muscle. EMG showed fibs/PSWs in all muscles, and just a few MUAPs in the rectus femoris muscle only. We believed that his recovery would remain limited, with only one of four quadriceps muscles showing any recovery at the time, and that he could benefit from decompression and possible nerve transfers. At surgery, his rectus femoris muscle had good contraction, but there was none in any other muscles. Dissection identified 2 large motor branches to each of his vastus medialis, lateralis, and gracilis muscles. The gracilis branches were transferred to the vastus medialis branches, one ETE and one SETS because of some evidence of recovery. Two sartorius branches were transferred to the vastus lateralis branches, both SETS because the vastus lateralis branch came from the same common branch to the rectus femoris, which was showing good recovery, and we believed that there was a good likelihood that some recovery of the vastus lateralis was still forthcoming. Almost 2 years later, he recovered MRC grade 4+/5 full knee extension, although a little atrophy persisted.

**Discussion**

**Obturator to Femoral Nerve Transfers**

Since the initial publication of this technique in 2010, only a few single cases have been published in the literature. Our prior report on obturator to femoral nerve transfers performed in the thigh described 2 patients. Since that time, no larger series have been reported. There has previously been concern regarding lower axonal counts in the obturator nerve than in the femoral nerve and its many motor branches. However, the clinical improvement demonstrated in our previous case series suggests that the anterior branch of the obturator nerve possesses a sufficient number of axons to power at least two quadriceps muscles. In fact, a recent anatomical study of 5 cadaveric limbs by Zhou et al. demonstrated a similar diameter of myelinated nerve fibers and axonal counts of the obturator nerve (11,358 ± 800) as compared to the rectus femoris (4,961 ± 655) and vastus medialis (6,666 ± 466) branches of the femoral nerve. The technique for obturator to femoral nerve transfers described in this study is an evolution of our original technique. With experience, we realized the anterior obturator nerve could be approached more proximally, as in a decompression for obturator syndrome, allowing for greater length of the gracilis and adductor longus branches as well as transfer of the adductor brevis motor branch. This allows for reinnervation of more than two of the quadriceps muscles as originally described. Adequate adductor function remains, as innervation to the adductor magnus is preserved in addition to the dual innervation to the adductor brevis via the posterior branch of the obturator nerve. There is no concern about injury to the posterior branch of the obturator nerve, as it is located deep to the adductor brevis muscle and is not visualized.

**Sartorius to Femoral Nerve Transfers**

Recently, use of the sartorius branches as donors for nerve transfer in femoral palsy was described. We now routinely check for the availability of sartorius branches as additional donors in all cases. These branches are often spared in the setting of a femoral nerve injury, perhaps because of their more proximal and superficial location. Proximity to the quadriceps branches also allows SETS transfer to be performed without the need for a nerve graft. The sartorius muscle acts as a secondary hip flexor, thigh adductor, and knee flexor and is widely considered expendable. Additionally, there are up to 5 to 6 nerve branches to the sartorius muscle, and many can be taken as available. Recent histological analysis has demonstrated axonal counts of an average of 672 nerve fibers (range 99–1850) in each sartorius branch. The ability of a nerve to compensate for a decreased number of nerve fibers up to a loss of about 80% of axonal counts is well known. We believe that despite the lower axon counts present in the sartorius branches than in the femoral branches, the use of multiple branches combined is enough to provide the 20%–30% threshold of normal nerve fibers needed to successfully reinnervate one or two quadriceps muscles.

**Surgical Algorithm**

Our current algorithmic approach to these patients is summarized in Fig. 5. Surgery is considered after observation of at least 6 months, as those who recover significant function usually do so by then. Therefore, most patients...
in our practice are not referred before that time, and unfortunately many are referred closer to or after 1 year when it has become clear that satisfactory recovery is not forthcoming. Once surgery is indicated, findings on EMG and intraoperative stimulation will inform the management. If there is no evidence of muscle reinnervation on EMG and no muscle contraction during intraoperative stimulation, then an ETE transfer is performed. If there is some although weak spontaneous recovery, as evidenced by MUAPs on EMG and MRC grade 1–3, but the improvement has stalled, decompression and SETS transfer are performed. Our rationale in these cases is that sufficient recovery of meaningful strength is unlikely, and SETS transfer will augment muscle reinnervation without the risk of downgrading existing function. The controversial cases are those in which MUAPs are severely reduced on EMG and intraoperative stimulation produces just a flicker or twitch. In such cases, an argument can be made for either ETE or SETS transfer based on the exact timing (earlier favoring SETS, later favoring ETE), severity of the reduction of MUAPs, and exact amount of intraoperative contraction noted. If the clinical “gut feeling” is that the likelihood of further meaningful spontaneous recovery is low and the contribution of the existing function is minimal, then we favor ETE transfer. In cases in which some of the quadriceps muscles are recovering but weak and others are showing no evidence of recovery, we will use both transfer techniques and perform ETE transfers to those with no recovery and SETS transfers to the others. Although this approach of combining nerve transfer techniques as well as donor nerves certainly confounds outcomes analysis and comparison, we believe it is most appropriate for the best functional outcome.

In general, we prefer to use sartorius branches first if available because they are dissected with the femoral nerve as well as their proximity to the other motor branches. However, availability is usually limited and rarely sufficient to reinnervate multiple quadriceps muscles. The gracilis and adductor longus motor branches of the anterior obturator nerve will provide the most length for transfer, but the adductor brevis branch can also provide a direct transfer if the target femoral motor branch can be neurolysed proximally with sufficient length to transpose to the obturator exposure. If SETS transfers are being done, the gracilis and adductor longus branches may provide enough length to reach the side of the femoral motor branches, but a nerve graft would be needed for the adductor brevis donor. As the axonal counts available from the anterior branch of the obturator nerve are higher than those of the sartorius, we prefer to use it for a greater proportion of quadriceps reinnervation.

Femoral Nerve Decompression for Pain

It has been our experience that many patients with femoral nerve injuries have significant neuropathic pain. In the operating room, we often encounter a significant compressive scar around the femoral nerve branches. Postoperatively, many patients notice significant improvement in their pain, which we attribute to decompression. We offer a femoral nerve decompression in our practice as a means of pain relief, even if the patient is not a candidate for motor reconstruction.

Study Limitations

Despite a larger sample size than any other previously
reported series of nerve transfers for femoral nerve palsy, this study is retrospective and is heterogeneous in terms of injury pattern and surgical approach. Femoral nerve decompression is performed as a routine and necessary part of the dissection and may also contribute to recovery. The surgical techniques include both ETE and SETS transfers using multiple donors. Therefore, it is difficult to ascertain how much improvement is attributable to decompression versus nerve transfer, and comparison of transfer donor and technique is also confounded. It is likely that improvements represent a combination of these techniques. Recovery seen immediately or early postoperatively is likely a result of decompression, representing either relief of ischemic conduction block (immediate improvement) or the remyelination of demyelinated axons (occurring 2–3 months postoperatively). Recovery from axonal regeneration through a nerve transfer takes many months and occurs in a delayed fashion. With the sartorius nerve branches now available as donors, cases of pure obturator to femoral nerve transfers are now few, as our approach is to utilize any and all donors available to reinnervate or augment as many quadriceps muscles as possible for maximal potential functional recovery.

SETs nerve transfer, despite being widely utilized in peripheral nerve surgery, is still controversial. There is no way to distinguish recovery from the SETs nerve transfer versus native proximal regeneration. This is a limitation of all studies that report outcomes following SETs nerve transfer. There was also no injury-matched control group. It is possible that some of the patients in this series would have had further functional improvement with a longer conservative course, but this is not supported by the literature.3 However, given the consistent and reliable success we have experienced with nerve transfers in these cases and the severely debilitating nature of femoral palsy, it is our opinion that it is better to operate early and not miss the critical time period for muscle reinnervation to avoid an irrecoverable deficit.

Conclusions

Femoral nerve palsy is a debilitating condition due to the loss of quadriceps muscle function. Until recently, few treatments were available for high femoral nerve palsy. With the availability of the obturator and sartorius motor branches as donors, nerve transfers can be used to reinnervate most if not all of the quadriceps muscles. The use of the techniques described in this paper in an appropriate time interval from injury makes it possible to reinnervate all four quadriceps muscles to maximize functional outcome.

Acknowledgments

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References


Disclosures

Dr. Moore is a consultant for the Checkpoint Surgical, Inc.

Author Contributions

Conception and design: Tung, Peters, Moore. Acquisition of data: Peters, Ha. Analysis and interpretation of data: all authors. Drafting the article: Peters, Ha. Critically revising the article: all authors. Reviewed submitted version of manuscript: all authors.
Approved the final version of the manuscript on behalf of all authors: Tung. Statistical analysis: Ha. Study supervision: Tung, Moore.

Supplemental Information

Videos

Previous Presentations
Presented as a poster presentation at the 2021 Annual Meeting of the American Society for Peripheral Nerve held virtually on January 10–17, 2021.

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