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TMR Surgery, Therapy, and Prosthetics:
Synchronizing Success

By Miki Fairley

On October 2, 2008, Hank Esmond of Bluffton, Indiana, an electrical lineman for Bluffton Utilities, was atop a utility pole when a surge of 7,200 volts of electricity shot through his body, causing extensive burns that resulted in 17 surgeries and the loss of both arms. Esmond, determined to regain his independence, was fiercely dedicated to his rehabilitation process, which included pioneering surgery, as well as advanced occupational therapy techniques and prosthetic technology.

Esmond was flown to the St. Joseph Hospital Burn Center in Ft. Wayne, where he spent about a month and a half. During most of that time, he was in a medically induced coma, according to a September 2009 article in Ft. Wayne-based Business People. Mercifully, Esmond has no recollection of the accident.

"In addition to fatalities, major high-voltage electrical trauma can produce devastating physical injuries," notes a health-and-safety fact sheet from the Energy Recovery Council. "Repeated removal of tissue, amputations, and extensive rehabilitation are common…. It is not unusual for treatment to require tissue removal over several days, and frequently the damage becomes significant enough to warrant amputation." Once the outer layer of skin is destroyed, large currents can pass through it and produce tissue damage, especially to skeletal muscle and nerves; healthy skin and fat often conceal injured muscles, nerves, and bone as well. "Thus, it is very difficult to accurately diagnose and localize tissue damage scattered throughout the current path before irreversible cell damage has occurred," the fact sheet says. It adds that it typically takes one to three days before the true extent of the damage can be recognized. This accurately describes what happened to Esmond. After a series of surgeries, Esmond ended up with a left shoulder disarticulation and a right transhumeral amputation.

Leading-edge techniques and technologies have converged in Esmond's rehabilitation care, including targeted muscle reinnervation (TMR) surgery; Otto Bock's DynamicArm TMR thought-controlled prosthesis; innovative occupational therapy; and new prosthetic-fitting techniques.

Esmond's groundbreaking team and the challenges they are meeting provide a dramatic picture of the new wave of rehabilitation care for persons with amputations. However, a key to successful rehabilitation is the patient—and Esmond's strong motivation and ability to learn quickly have won the admiration of his rehab team. Brooke O'Steen, OTR/L, has worked with Esmond since the beginning of his recovery and rehabilitation journey. In describing Esmond, O'Steen simply says, "He's awesome!"

Pat Prigge, CP, recalls a story that epitomizes Esmond's determination and intelligence. Prigge, who is the clinical upper-extremity specialist at Advanced Arm Dynamics (AAD) of the Midwest, Waterloo, Iowa, has been working with Sam Santa-Rita, CP, LP, owner of Superior Rehabilitation Techniques (SRT), based in Ft. Wayne, on Esmond's prosthetic care. "When we were teaching him how to operate his prosthesis for his transhumeral side, we told him it would take a little time to learn since we needed to use a very complicated control method to make it work. I told him, ‘Don't expect to be able to pick up a paper cup today—that's going to come in time.' Well, while I was talking to his therapist, Hank comes back over and hands me a paper cup!"

As part of field trials, Esmond was fitted with the beta version of Otto Bock's DynamicArm TMR on his shoulder-disarticulation side. The prosthesis, especially designed to take advantage of the more intuitive control options provided by TMR surgery, can handle up to eight myoelectric inputs. Esmond uses a conventional myoelectric prosthesis on his transhumeral side. In February, he was fitted with one of the first two commercial models of the prosthesis. The control programs are totally different for his left and right sides, O'Steen notes. "He's had to learn to operate them simultaneously for bimanual tasks, and he's done amazingly well."

"He's doing something [with his right-side prosthesis] that most patients probably wouldn't tolerate," Prigge says. "He's running a full electric system with a single electrode, a second input site, and a linear transducer. That's complicated in itself, but he's doing really well." Prigge adds, "The reinnervation surgery and the more intuitive control pattern with his shoulder disarticulation side should help him better supplement what he is already doing with the right side." The fact that Esmond is almost ambidextrous—he eats and writes with his left hand, but plays sports right-handed—may also contribute to his unusual success in using bilateral prostheses.

The DynamicArm TMR can utilize up to eight myoelectric inputs; Esmond's recently fit prosthesis is currently programmed to access four sites, and as he gains more accurate control of other muscle sites, a fifth and then a sixth site will be added into the program.

"The four-site system is a stepping stone to where we want to go," Prigge explains. "He's got strong, successful reinnervated sites, but it takes time to learn how to access those muscles." The six essential movements are elbow flexion/extension; wrist supination/pronation, and hand open/close. By merely thinking about it, Esmond can now flex or extend his elbow while opening or closing his hand. He also can control wrist pronation/supination by utilizing a switch over the top of his shoulder—movements that will be controlled simply by thought once he is able to fully use his fifth and sixth myoelectric input sites.

Prigge likens these cutting-edge rehabilitation advances to a cascade, rather than a convergence. "The TMR surgery seems to have been first, then manufacturers stepped up and created new products to utilize the new signal sites. Now fitting techniques need to be modified to adapt to the new technology. It's a whole cascade of things building up into something new and unique, with a whole slew of new challenges. We've got to do things we've never done before."

TMR Surgery Paves the Way

TMR surgery provides the platform for intuitive, thought-controlled prosthetic function. Pioneered by Todd A. Kuiken, MD, PhD, director of the Neural Engineering Center for Artificial Limbs (NECAL) at the Rehabilitation Institute of Chicago (RIC), Chicago, Illinois, TMR is a surgical technique by which spare muscles—generally in the chest—are denervated and then reinnervated with residual nerves of the amputated limb. The reinnervated muscles provide myoelectric signals that correlate to the original nerve functions of the missing limb, allowing for intuitive, simultaneous control of upper-limb movements, such as extending the elbow while opening the hand, rather than the sequential switching required by conventional myoelectric prostheses. TMR bypasses another problem associated with traditional myoelectric control, which accesses signals generated by nerves and muscles not normally used for upper-limb functions, thus requiring more conscious thought by the user.

"With my previous prosthesis, I could only do one movement at a time and had a lot of switching to do," Esmond says. "Now I just think about opening my hand and it opens, or straighten my elbow and it straightens." Another advantage of TMR is that it does not require any implants, thus reducing infection risk and eliminating the problem of tissue immune response to foreign bodies.

In some cases, a serendipitous effect of TMR surgery has been a restoration of sensory feeling in the missing limb when the reinnervated area is touched. A study, "Sensory Capacity of Reinnervated Skin after Redirection of Amputated Upper-Limb Nerves to the Chest," by Kuiken, Paul D. Marasco, PhD, and Aimee E. Schultz, MS (Brain, Volume 132, Number 6, June 2009), explains, "The sensory afferents of the redirected nerves reinnervate the skin overlying the transfer site. This creates a sensory expression of the missing limb in the amputee's reinnervated skin." This effect opens an exciting potential pathway to integrate sensory feeling into a prosthesis for greater function and as well as helping the amputee feel that the prosthesis is more of an integral part of his or her body.

What lies ahead for TMR surgery? "We're continually refining the surgery, finding ways to do it easier and better," Kuiken says. "We are subdividing the nerves and transferring them to different places to hopefully obtain more information from them and enable more effective sensor placement."

A study by Kuiken and others on outcomes for the first 30 TMR patients worldwide, presented during the Annual Meeting and Scientific Symposium of the American Academy of Orthotists and Prosthetists (the Academy) in February, concluded that the surgery is highly reliable in producing additional myoelectric sites for hand and elbow control. According to the study, "Postoperative complications are minimal and consist primarily of rare failed nerve transfers and frequent transient increases in phantom limb pain."

Componentry Steps up to the Plate

Manufacturers now face the challenge of developing technology that maximizes TMR surgery's prosthetic potential. Otto Bock's DynamicArm TMR and the Boston Digital Elbow from Liberating Technologies Inc. (LTI) have been used for TMR patients. Prigge, commenting on the DynamicArm TMR, used by Esmond, especially appreciates the software. "It's so flexible," he says."I haven't really found a limitation in being able to adjust the software for any fitting that I've done." Prigge can take justifiable pride in the software. Previously the director of prosthetics education at Otto Bock, he, along with Otto Bock's other clinicians, was involved in the early stages of developing the DynamicArm technology, providing clinical input to its engineers and for its preliminary trials.

Those Slippery Signals: A Fitting Challenge

There are challenges in fitting a patient who has undergone TMR surgery, Prigge notes. Among various TMR patients, the TMR sites are not always in the same place, often are placed with differing orientations, and are on different underlying tissue. Thus, each patient may require a different approach. "It's not like a transradial case, where you know you have wrist extensors and flexors. With TMR, you know that when the person thinks ‘biceps flex,' a chest muscle will move, but where those sites are supposed to be and where they will be optimized is not a refined science at this point." As the nerves regenerate, the strongest myoelectric site might shift more than an inch with the same conscious thought of ‘hand close,' Prigge points out, adding, "So, if you fit early, plan on shifting those electrodes around." Although muscle twitches generally begin between six and eight weeks post-surgery, Prigge says, "we wait awhile to get those muscle sites stabilized, sufficiently strong, and well enough separated to have a successful prosthetic fitting."

In addition, TMR surgery often makes the muscle and soft tissue underlying the sites hypermobile, Prigge says. Exacerbating the hypermobility is that fat tissue often is removed between the skin and the muscle site in order to strengthen the signal. "When the muscle moves, it tends to pull the skin and the attached electrodes with it." Although the socket and the electrodes do not move, the skin does. If the skin slides sideways under an electrode, it causes a static signal and the arm becomes uncontrollable. In TMR, you see hypermobile tissue almost 100 percent of the time."

An extremely intimate fit helps to control the electrode movement. The AAD team also is working on some ideas for keeping tension on the electrode site while still allowing movement underneath it. "We're working on some concepts—not perfected yet—that might allow for the electrode to move separately from the frame," Prigge says. "We're putting our brains together to come up with a new idea to solve a new problem."

Occupational Therapy: Creative Solutions

Working as Esmond's therapist has been virgin ground for O'Steen—somewhat akin to learning how to swim by being thrown into the deep end of the pool. "I had never worked with an amputee before," O'Steen says—and her first amputee patient was a high-level bilateral who would be undergoing a new surgical technique and using advanced prosthetic technology! However, O'Steen rose to the challenge, working with Esmond on range-of-motion (ROM), coordination, activities of daily living (ADL), and home modifications, among other issues.

"Hank's personality and motivation have enabled him to succeed," O'Steen says. "And he learns things so fast!" Esmond has mastered many of the complex tasks of daily living, plus he coached his son's T-ball team this year. Although Esmond's warm and loving family, including his wife, Jenny, and children, Conner, 13; Olivia, 11; and Grant, 8, is more than ready to lend assistance when needed, Esmond is strongly determined to be as independent as possible. Modifications to Esmond's home have helped him achieve more independence. For instance, an innovative device in his shower stall, the Tornado Body Dryer (www.tornadobodydryer.com), provides a soothing swirl of warm air that envelops him from head to toe, enabling him to dry off without a towel or assistance from someone else. Other adaptations to Esmond's home include a foot-operated soap dispenser, a computer mouse he can move with his foot, and a speakerphone that has large buttons so that Esmond can operate it with his toes. Esmond is also working with a certified trainer to learn to drive his truck with adaptations. They are currently exploring whether they can minimize the adaptations so that others also can drive the vehicle.

Shawn Swanson, OTR/L, national director of occupational therapy services for AAD, came aboard in February 2009 to help O'Steen find solutions so that Esmond can be independent in everyday life, with or without a prosthesis. Because this was O'Steen's first upper-limb-loss patient, Swanson provided assistance and resources regarding preprosthetic rehabilitation as well as high-level bilateral prosthetic training and TMR therapy. "Along with three on-site visits to Indiana, we took advantage of today's computer technologies and had several web-based conference calls to make sure Brooke, Hank, and Hank's family felt comfortable with the rehabilitation plan," Swanson says. "It was a real team effort, including Hank and his family, the prosthetist, the technicians, and the therapists, in coming up with creative ideas to help Hank achieve independence."

Although these challenges are common to high-level upper-limb amputees, TMR patients face some unique ones as well. Occupational therapists "have to think outside the box," Swanson says. "Preprosthetic and prosthetic training is going to be a little different. Generally, patients do visual imagery and muscle contractions on their own for several months. After the nerves have regenerated at about the five- or six-month mark, we do more visual-feedback evaluation and training. The muscle-site evaluation is done by palpating the residual limb and placing five or six electrodes where the contractions are felt to locate the best signal sites. We try to look for good separation of signals for such movements as ‘hand open' without a lot of crosstalk or feedback from muscles that might be trying to contract at the same time." An important goal is strengthening reinnervated muscles to generate electrical signals detectable by surface electrodes. Although this goal is similar to developing traditional myoelectric control, the exercises are slightly different because of the redirected pathways from the brain to the targeted muscles. "As a result, the occupational therapist must thoroughly understand peripheral nerve distribution, including which nerves are anticipated to reinnervate which muscles, in order to perform the appropriate strengthening exercises.

Neither the surgeon nor the OT can be certain which nerve fibers will reinnervate the host muscle...," notes a 2009 article, "Occupational Therapy Protocol for Amputees with Targeted Muscle Reinnervation," by Kathy Stubblefield, OTR/L; Laura Miller, PhD, CP; Robert Lipschutz, CP; and Kuiken, published in the Department of Veterans Affairs' Journal of Rehabilitation Research and Development (www.rehab.research.va.gov/jour/09/46/4/pdf/stubblefield.pdf). Once multifunction prosthesis training begins, having the prosthetist available is helpful, since frequent adjustments to electrode gains, EMG thresholds, and electrode location in the socket are necessary, the article notes.

"While waiting for the nerves to reinnervate, patients can use their regular prostheses, being careful not to use co-contraction for switching from one component to another, as we need to encourage isolation of the native and reinnervated sites," Swanson explains.

The rehabilitation training period for TMR patients is generally longer and more extensive, but the end result—faster, more efficient, easier, intuitive prosthetic control—is considered worth it.

Evolving toward Tomorrow

Although Star Wars hero Luke Skywalker didn't need much time to adapt to his prosthetic hand, thought-controlled prosthetic use in real life today generally requires intense, dedicated effort by the user, the prosthetist, the therapist, the surgeon, and the physiatrist, not to mention prosthetic manufacturers' development of innovative new componentry. The trailblazing rehabilitation techniques being used to help Esmond and others with high-level upper-limb amputation to achieve optimal function and independence are still works in progress—but they are definitely on their way. And who knows what dazzling breakthroughs will appear on the horizon as today's experimental technologies become tomorrow's clinical realities.

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