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BRIEF REPORT

Robotic Leg Control with EMG Decoding in an Amputee with Nerve Transfers

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SUMMARY

The clinical application of robotic technology to powered prosthetic knees and ankles is limited by the lack of a robust control strategy. We found that the use of electromyographic (EMG) signals from natively innervated and surgically reinnervated residual thigh muscles in a patient who had undergone knee amputation improved control of a robotic leg prosthesis. EMG signals were decoded with a pattern-recognition algorithm and combined with data from sensors on the prosthesis to interpret the patient's intended movements. This provided robust and intuitive control of ambulation — with seamless transitions between walking on level ground, stairs, and ramps — and of the ability to reposition the leg while the patient was seated.

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CASE REPORT

A 31-year-old man underwent a knee-disarticulation amputation in 2009, approximately 36 hours after a motorcycle collision. During the amputation surgery, two nerve transfers were performed to prevent neuroma formation.[1] The severed sciatic nerve was separated into its tibial and common peroneal branches. Small nerve branches to the distal portions of the residual semitendinosus muscle and the long head of the biceps femoris muscle (Fig. 1) were located and cut where the nerves entered their respective muscles. The tibial nerve branch was then sewn over the motor point on the semitendinosus, and the common peroneal nerve branch was sewn over the motor point on the long head of the biceps femoris, thus allowing the transferred nerves to reinnervate these hamstring muscles. This surgery is analogous to targeted muscle reinnervation (TMR) surgery that is performed as part of arm amputation to improve the control of motorized arm prostheses.[2] As expected from our experience with TMR, discrete contractions in reinnervated muscles developed after a few months. When the patient attempted dorsiflexion of his missing foot, a contraction could be seen and palpated in the distal semitendinosus. Similarly, contraction of the distal long head of the biceps femoris occurred when he attempted plantarflexion of his missing foot.

METHODS

EVALUATION OF EMG PATTERNS AFTER REINNERVATION

The patient gave written informed consent for participation in the institutional review board–approved experiments described here, which took place between January 2010 and October 2012. The quality of the EMG signals from the patient's residual limb was investigated with the use of high-density EMG, which has been

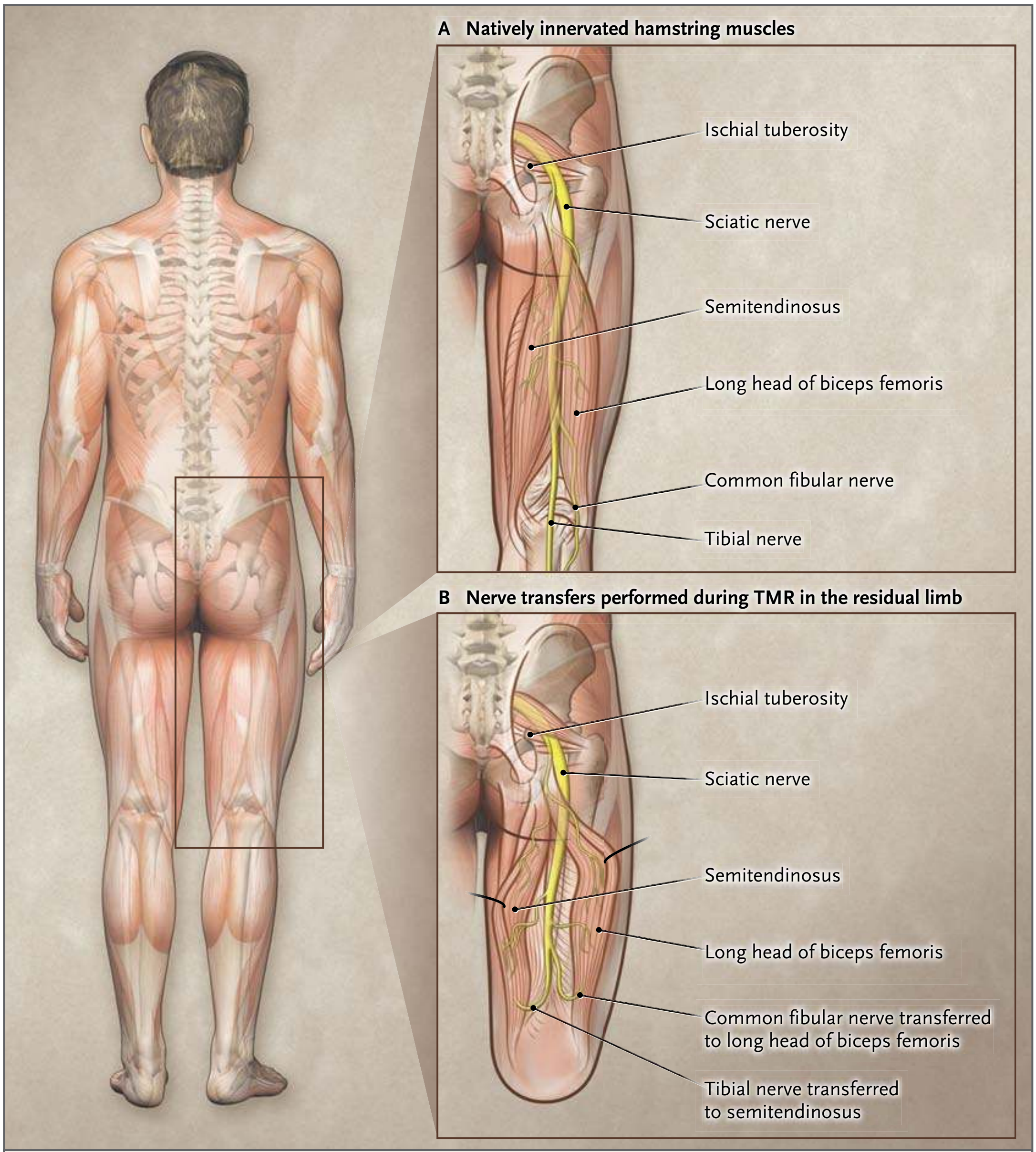

Figure 1. Natively Innervated and Surgically Reinnervated Residual Thigh Muscles.

Posterior views of the anatomy of the upper thigh show natively innervated hamstring muscles (Panel A) and nerve transfers performed during targeted muscle reinnervation (TMR) surgery (Panel B) in the residual limb.

used to interpret EMG signal quality in upper-limb amputees after TMR.[3] A cylindrical grid of 96 electrodes, with a center-to-center distance between adjacent electrodes of approximately 25 mm, was placed on the distal residual limb. EMG signals were collected with the use of a TMS Refa 128 measurement system (Twente Medical Systems International) as the patient attempted knee flexion, knee extension, ankle plantarflexion, and ankle dorsiflexion. Contractions were held for 5 seconds at medium intensity and were repeated 10 times. The root-mean-square EMG signal measured at each electrode for each contraction type was color-coded according to amplitude for qualitative interpretation.

To evaluate the contribution of EMG signals from natively innervated and surgically reinnervated muscles to robotic prosthesis control, a pattern-recognition system was tested in a virtual environment with the patient in a seated position.[4] Ten bipolar surface electrodes were placed over eight natively innervated residual limb muscles (proximal biceps femoris, rectus femoris, vastus lateralis, vastus medialis, sartorius, gracilis, adductor magnus, and tensor fasciae latae) and the two reinnervated muscle segments. The patient performed the attempted movements described above as well as femoral rotation (in and out) and tibial rotation (in and out). The patient's ability to control the virtual device in real time (i.e., the percentage of completed motions in the virtual-environment test) with the use of a pattern-recognition system was compared with previously reported data on four persons who had undergone transfemoral amputation without TMR surgery (non-TMR amputees).[4]

EVALUATION OF ROBOTIC PROSTHESIS CONTROL DURING AMBULATION

To investigate the effect of adding EMG control during various ambulation activities, the patient was first taught to walk with a robotic prosthesis that is designed to have a set of impedances (joint stiffnesses) for each ambulation mode, as described by our collaborators at Vanderbilt University.[5,6] The prosthetic leg, including the battery and embedded control system, has a mass of 4.7 kg. The knee and ankle joints are actuated in the sagittal plane with the use of two Maxon EC30 motors (Maxon Motor). The patient wore a socket with a supracondylar suspension system. During a 3-hour accommodation session, the prosthesis was configured so that the patient could ambulate safely and comfortably in each of the following modes: walking on level ground, walking up or down a ramp with a 10-degree slope, and ascending or descending a set of stairs with a reciprocal gait. In a separate session, the patient completed 20 repetitions of a circuit that included all ambulation modes, during which a researcher remotely transitioned the prosthesis between modes when the foot made contact with the ground (heel contact) and was lifted into the air (toe off), using a wireless key fob.

Thirteen mechanical sensors are included in the mechanical design of the prosthesis (a three-axis accelerometer, a three-axis gyroscope, and sensors for vertical load, knee and ankle position, torque, and velocity). EMG and mechanical-sensor data were processed with the use of a phase-dependent pattern-classification method before heel contact and before toe off.[7] A dynamic Bayesian network was used for classification.[8] The patient ambulated freely around the laboratory and completed 10 additional circuits, during which transitions between ambulation modes in the prosthesis were performed automatically under two conditions: with the use of both EMG and mechanical-sensor data to control the prosthesis and with the use of mechanical-sensor data alone to control it.

RESULTS

EMG PATTERNS AFTER REINNERVATION

The reinnervated hamstring muscles generated robust EMG signals, especially during contractions corresponding to ankle movements (Fig. 2A through 2D). Marked coactivation of reinnervated muscles was noted when the patient performed knee flexion (Fig. 2A). Each attempted motion generated distinct EMG signal patterns, suggesting that accurate pattern-recognition control was feasible.

The classification accuracy of the patient's attempted movements was 96.0% with a virtual system configured to control ankle plantarflexion and dorsiflexion and knee flexion and extension, and the accuracy was 92.0% with a system additionally configured to control tibial rotation and femoral rotation. Classification accuracies for these attempted movements were 91.0±4.7% and 86.8±3.0%, respectively, in non-TMR amputees.[4] This translates into an improvement in absolute accuracy of 5.0 percentage points and 5.2 percentage points, respectively — and, more important, into a 44% and 39% reduction in the error rate; these findings indicate that TMR improves real-time pattern-recognition control. The patient also completed virtual movements much faster than did the non-TMR amputees (Fig. 2E and 2F) and could reliably reposition both a virtual avatar (i.e., a graphical representation of the joint) and a robotic knee-and-ankle prosthesis in real time (Video 1, available with the full text of this article at NEJM.org).

Videos showing the patient using the robotic prosthesis are available at NEJM.org

ROBOTIC PROSTHESIS CONTROL DURING AMBULATION

EMG data from the residual limb and mechanical-sensor data produced a unique stride pattern for each ambulation mode. The inclusion of EMG information increased the accuracy of the control system. With the use of mechanical-sensor data only, the overall real-time error rate (i.e., the rate of movement misclassification) across all ambulation modes was 12.9%. The real-time error rate

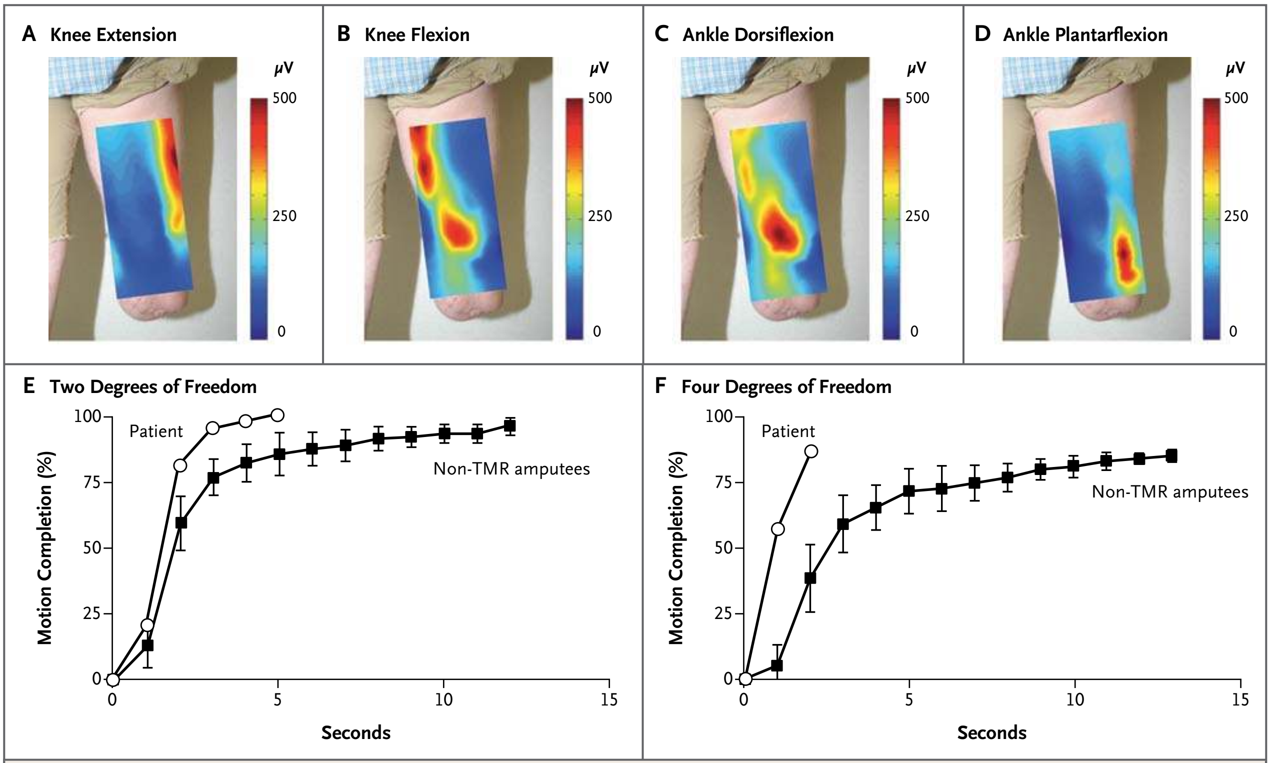

Figure 2. **Evaluation of Muscle Reinnervation Patterns.**

Photographs show an anterior view of the patient's residual limb with superimposed maps of electromyographic (EMG) signal amplitude corresponding to knee extension (Panel A), knee flexion (Panel B), ankle dorsiflexion (Panel C), and ankle plantarflexion (Panel D). Colors indicate the level of EMG activity: areas of high EMG activity, corresponding to strong muscular contractions, are red; areas with little EMG activity are blue. Real-time testing showed that the patient completed motions faster than did non-TMR transfemoral amputees[4] for both two degrees of freedom (ankle plantarflexion and dorsiflexion and knee flexion and extension) (Panel E) and four degrees of freedom (ankle plantar flexion and dorsiflexion, knee flexion and extension, tibial rotation, and femoral rotation) (Panel F). I bars indicate standard deviations.

decreased to 2.2% when EMG information from the natively innervated muscles was added. The error rate decreased further, to 1.8%, when the EMG information from reinnervated muscles was added, and the patient was able to ambulate robustly and transition seamlessly between ambulation modes with the use of this TMR-enhanced, intuitive control system.

When mechanical-sensor data only were used, the majority of errors caused relatively small perturbations that were noticeable to the patient. Critical errors — defined as errors resulting in perturbations that might cause the patient to fall — occurred during 2% of trials. No such critical errors occurred with the use of the TMR-enhanced control system. With the use of this TMR-enhanced combination of mechanical-sensor and EMG information, the patient was also able to walk safely outdoors and to climb and descend multiple flights of stairs with the robotic leg prosthesis (Fig. 3 and Video 2).

DISCUSSION

To change the ambulation mode in commercially available motorized prosthetic knees, the user must press buttons on a key fob or perform a set of predefined, exaggerated motions.[9,10] Furthermore, these devices must be manually repositioned when users are seated. The leg prosthesis used in this study showed control accuracy with mechanical sensors alone, albeit when controlling a limited number of ambulation modes, but several errors occurred that could put users at risk of falling. User safety is of paramount importance; thus, error rates must be very low, and prevention of even a few errors has clinical significance.

With the control strategy that we used, EMG signals from natively innervated muscles were decoded with a pattern-recognition algorithm and combined with data from sensors on the prosthesis to interpret the patient's intended movement. This resulted in a reduction in the error rate from 12.9% to 2.2%. We expected a reduction in the error rate with the use of EMG data from natively innervated muscles, because all ambulation modes required activation of knee muscles; however, we were surprised by the magnitude of the reduction. The error rate was further reduced, to 1.8%, with the use of the TMR-enhanced control system.

The errors that did occur affected the patient's stability to varying degrees. Each ambulation mode was set up with the use of an impedance-control paradigm to generate the knee and ankle torques.[11] The control system predicted the patient's desired ambulation mode, which in turn instantaneously dictated the impedance settings. The degree of disturbance created by system error corresponded to the level of mismatch between the impedance settings for the actual activities and those for the predicted activities. Because the impedance settings for some ambulation modes were very similar, this resulted in a very forgiving control system: many errors, such as misclassifications between walking and ramp ascent, were not noticeable to the patient.

Moderate disturbances that the patient noticed but could tolerate occurred during misclassifications between walking on level ground and descending stairs or a ramp. Errors that caused moderate disturbances were reduced with the use of the TMR-enhanced system, as compared with the use of EMG signals from natively innervated muscles only. Thus, although the additional reduction in the error rate was small, the improvement was clinically relevant. Finally, errors during the transition from any ambulation mode to stair ascent caused large, critical disturbances that were difficult for the patient to recover from safely. This type of error did not occur when EMG data — either from natively innervated muscles only or from the TMR-enhanced muscle set — were added to the control system.

The patient perceived that the TMR-enhanced system provided intuitive control during ambulation and non–weight-bearing activities. The reduced error rate enabled him to ambulate confidently and transition seamlessly among all modes with near-normal gait kinematics. The patient provided especially positive feedback when he ambulated freely outside the laboratory and entered adjacent buildings without difficulty, without using handicapped-accessible entrances. In the non–weight-bearing mode, he could reliably control both joints, which is useful for repositioning the prosthesis to increase comfort, dressing, and preparing for transfers into or out of chairs or vehicles.

Figure 3. Stair Ascent with Reciprocal Gait with the Use of the TMR-Enhanced Control System.

Obtaining robust EMG-control information is difficult, because surface EMG signals are more variable and noisy than mechanical-sensor data. Some EMG channels, such as those from the rectus femoris, were contaminated by substantial motion artifact at heel contact, resulting in large-amplitude noise at the start of each stride. Real-time filtering techniques may be used to alleviate this noise; because it was a consistent part of the EMG patterns across trials, it did not adversely affect system accuracy. The overall patterns of EMG activity for each ambulation mode were distinct, and the low rates of classification errors indicate that the patterns of EMG activity were repeatable.

Although this study establishes the feasibility of using EMG signals to improve the control of robotic leg prostheses, several challenges remain in making the control system clinically viable. First, the system relies on the recording of high-quality EMG signals through electrodes, which must remain in full contact with the residual limb during walking, without becoming uncomfortable for the user. This is challenging, because movement of the residual limb with respect to the socket creates movement artifact in EMG signals and can cause chafing or pressure sores at electrode contact points after prolonged use. Second, improvements in the pattern-recognition classification algorithms and the mechanical sensor system are necessary. Finally, the robotic prosthetic leg must be made more reliable, quieter, smaller, and lighter to benefit larger numbers of amputees.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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