that are not clearly beneficial. The fiscal health of Medicare and the federal government will hinge on the new president and Congress making these difficult decisions wisely.

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Taking Control of Prosthetic Arms

Gerald E. Loeb, MD

PROSTHETIC LIMBS AIM TO REPLACE WHAT IS MOST OBviously missing—the mechanical function and physical appearance of bones, muscles, and skin. Mechatronics—the fusion of advanced motors, electronics, and servocontrol and power systems—is enabling the development of highly articulated prosthetic limbs capable of complex movements. But still missing are the parts that cannot be seen—the bidirectional flow of information between the limb and the central nervous system, which enables dexterous movements.[1] The absence of interfaces with the nervous system has been less of a problem for advanced lower-extremity prostheses, because the functional abilities of these prostheses are much more limited and because these devices can take cues by sensing mechanical events initiated by the intact parts of the body (eg, stump and contralateral leg).[2] Failure to develop practical neural interfaces for command and sensation in the upper extremity will lead to a repeat of the early disappointment with myoelectric arms.[3] Those limbs were (and continue to be) difficult to control, requiring intense user concentration to move one joint at a time with little or no control of velocity or force.

The paradox for myoelectric control is that as more control is needed, fewer myoelectric channels are available. Higher levels of arm amputation mean fewer separately recruited bits of muscle, and their natural functions are more remotely related to those being replaced by the mechatronic limb. Kuiken et al[4] pioneered a way around this paradox by rewiring the neuromuscular innervation, following up on a suggestion made in passing in an early review of potential approaches to this problem.[5]

In this issue of *JAMA*, Kuiken et al[6] describe the use of the advanced signal processing required to convert easily recorded multichannel electromyogram signals into functionally useful postures and movements of advanced prostheses with multiple actuators. The speed as well as accuracy of the movements represent substantial improvements over previous myoelectric systems. Even more important, however, is the ease with which patients learned to perform tasks requiring coordinated motion in more than one joint. This substantial advance reflects the synergy of simultaneous improvements to both the signal source and the processing algorithms.

Targeted muscle reinnervation (TMR) techniques are producing promising results, but several obstacles may hamper their widespread clinical deployment. Prosthetic system design must be tailored for each patient, and surgical technique will have significant effects on results obtained, as noted in the report by Kuiken et al.[6] Targeted muscle reinnervation involves substantial surgery and recovery time for reinnervation, although this could be integrated with the initial amputation and repair procedures in at least some patients.

Selecting postures and movements for the unloaded limb is only the first step in developing a command and control system in which the mechatronic limb can interact in a forceful but compliant manner with external objects. The command signals from reinnervated muscles (or any other source) will have to be integrated electronically with the prosthetic equivalent of somatosensory feedback. During the devel-

See also p 619.

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opment of TMR, Kuiken et al[7] made the fortuitous discovery that cutaneous afferents originally projecting to the hand tended to reinnervate denervated skin over the reinnervated muscles. If prosthetic hands can be fitted with effective tactile sensors,[8,9] their feedback could be used to provide conscious perception of touch via mechanical stimulation of the reinnervated skin. Perhaps even more important will be rapid, automatic adjustments of the actuators in response to sensory feedback, replicating the role of the spinal cord to coordinate the complex musculoskeletal linkage of the biological limb.[10,11] Such prosthetic systems will be even more complex and must be developed for a relatively small population of patients in an increasingly cost-conscious health care system.

Over the years, a great deal of effort has been expended by many research groups pursuing other approaches, most of which involve direct recording and stimulation of central neurons[12] and peripheral neurons.[13] Such technologically elegant interfaces are still limited by their own complexity and by the idiosyncratic reactions between the human body and microscaled synthetic devices.[14] In theory, these central neural interfaces might provide even more information for command and perception than can be obtained peripherally through targeted sensory and motor reinnervation. In practice, each of these alternatives will be judged by their users and by payers according to demonstrated costs and benefits in activities of daily living.

Kuiken et al[6] have reported on an exciting and promising work in progress, with many opportunities available to improve both the technology and the clinical implementation. Such revolutions develop slowly at best, but their effects tend to be profound. With increasing functional capabilities, patients with upper-extremity amputations may derive exceptional benefit from prosthetic arms, just as legions of patients with lower-extremity amputations now lead remarkably normal and even athletic lives.

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