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JRRD Guest Editorial

# Progress on stabilizing and controlling powered upper-limb prostheses

## INTRODUCTION

While the *Journal of Rehabilitation Research and Development* (*JRRD*) is often a repository for research conducted with a large subject population to compare and validate the devices and treatments used in rehabilitation, it is also a means to keep clinicians and researchers up to date on the development of new devices and treatments. This issue, addressing the problem of upper-limb loss, emphasizes the device-development side of *JRRD*'s mission. Compared with other forms of disability, upper-limb loss is relatively rare, and finding a large enough group of subjects is often difficult for studies that help researchers assess whether they are going in the right direction. When developing new devices are being developed, careful feasibility studies are important. Much that is reported here is preliminary and based on relatively few subjects. My objective is to quantify the state of development so that other researchers can move the field forward knowing which directions are the most promising.

This issue of *JRRD* began with a collection of articles about any problems associated with upper-limb prostheses. However, I quickly realized that the researchers submitting articles were overwhelmingly interested in the control of powered prostheses. During the last decade, great advances have been made in acquiring more information from myoelectric signals. Many of the articles in this issue address the recognition of patterns within surface myoelectric signals to first discern the user's intent and then implement that intent in a working device. A careful look at this research shows that myoelectric control, whether of the simple two-muscle type or the more sophisticated pattern-recognition control of multiple degrees of freedom (DOFs), has a serious flaw—no inherent feedback of position, speed, or force is associated with myoelectric control. This means that the reader should pay particular attention to the articles that report on ways to use the relative motion of remaining body parts to achieve control with feedback. In the articles in this issue and in others that I will refer to, the research goal is intuitive control of prostheses. Users should have to think only about what they want to do, not about how to control their prostheses.

## WHAT IS THE PURPOSE OF AN UPPER-LIMB PROSTHESIS?

The answer depends on the goal of the wearer. For most users, a prosthesis restores body image and cosmesis and also replaces as much function of the intact limb as possible; however, it must do so with the least possible discomfort and inconvenience. A successful prosthesis is one that can be incorporated into the user's lifestyle almost seamlessly. Just with this simple statement, many trade-offs become apparent. But what are the trade-offs between function and cosmesis? How much weight can be added to increase function without compromising comfort? How important is the stability of the socket interface? The articles in this issue show that researchers are aware of these trade-offs as they try to improve one aspect of prosthesis design at a time. In the end, no prosthesis will ever be "best." Users will always want to choose their own trade-offs. Thus, researchers must not only work to improve the individual prosthetic components and control schemes but also place their new devices on sufficient numbers of users so that the relative efficacy of the individual devices and control schemes can be determined. Such comparing of capabilities will allow the market to eliminate those devices that do not help enough users to justify their cost to society.

## MAKING MYOELECTRIC CONTROL INTUITIVE

If a person loses the arm just above the elbow and if the muscle ends are properly attached to the distal humerus, the remaining muscles will respond to an attempt to move the missing forearm. Trying to raise the forearm will result in contraction of the biceps (and the brachialis, if still present). Likewise, an attempt to extend the forearm will result in contraction of the triceps. Suppose that myoelectric sensors are used to detect these contractions and the resulting signals are used to control motion of a powered elbow. The result can be simple speed and direction control or the more sophisticated control that also stiffens the joint during cocontraction of these muscles as in the intact limb. What is still lacking is any proprioception to indicate to the user where the limb is in space. For most users, contracting the appropriate muscles to control a particular motion will require less attention than other control methods, and thus we may choose to call this control intuitive. Qualifying it as intuitive myoelectric control is more accurate. The essence of this type of control is that the nerves and muscles associated with a particular motion are used to activate that same motion in the prosthetic limb. Several articles in this issue report on progress toward this level of intuitive control. However, positional feedback is so important that other articles revisit ways to control joint motion with schemes that have proprioceptive feedback. By using the relative motion of body parts for control, one can move a joint while receiving feedback as to speed, position, and even the degree of torque opposing motion of the artificial joint. Several articles address this form of control.

## HOW CLOSE ARE WE TO INTUITIVE SIMULTANEOUS MYOELECTRIC CONTROL OF THE WRIST AND HAND?

I have personally observed children with both congenital and acquired transradial amputations while they moved a hand and wrist on a computer screen. The subjects were trained with contralateral stimulation. They were asked to attempt moving their nonexistent hand and wrist in a mirror image of simultaneous motion of their intact limbs. Data were collected from multiple myoelectrodes over both forearms and then used to train a computer algorithm. A short time later, the subjects were able to use signals from the remnant of the missing limb to control motions of the wrist and to open and close a hand on the computer, albeit not simultaneously [1]. From observing these experiments, I am convinced that both the wrist and hand can be controlled simultaneously. Articles in this issue show that work on intuitive control of multiple DOFs is being performed at many institutions. I believe that all these researchers have the same goal in mind. They are looking for practical ways to control the wrist and hand simultaneously and with sufficient speed that the users will not perceive unacceptable time lags. The reader should peruse the references in the articles in this issue to fully comprehend the extent of this work. In addition, an article by Nielsen et al. shows that researchers are getting closer to the goal of providing simultaneous proportional control to the artificial wrist and hand [2]. In short, many people are working toward intuitive control of the wrist and hand.

## IS HARDWARE AVAILABLE TO IMPLEMENT INTUITIVE CONTROL?

Several prosthetic suppliers have announced that they will offer wrists that incorporate both prosupination and flexion-extension. The article by Kyberd et al. in this issue discusses a practical approach to designing a two-function powered wrist [3]. Earlier development work by Kyberd et al. is also worth perusing [4]. Such a wrist requires two motors, and in the mechanism discussed, both motors are used simultaneously, halving the required motor mass. With actual hardware in hand, they were able to explore some of the practical issues of using pattern recognition to control both wrist motions. (Of course, any occupational therapist would remind the research community that the missing radial-ulnar deviation DOF is just as important as the two supplied.) Because another motor would be needed, this DOF is not likely to be added any time soon.

The second component of the hand-wrist system is also in a period of transition. Commercial hands have traditionally employed a thumb member moving with respect to fingers one and two about a parallel axis, lining up the thumb between the tips of the two fingers to give a sort of three-jaw chuck grip. Today, several firms are introducing hands with fingers that have added a single phalangeal-interphalangeal joint. Typically, the fingers in these hands wrap around an object independently until all fingers experience similar resistance to further motion. In some hands, the thumb member can be rotated into two positions, and by timing the motion of the thumb with respect to the remaining fingers, one can achieve many grip patterns. These hands present a new challenge to the control community. While they offer a number of grip patterns, they do so by requiring the user to employ some combination of contractions or full opening of the hand to preselect a particular grip. This is a long way from intuitive control of the individual fingers and the thumb. Just as pattern recognition seems to be giving intuitive control to the wrist and a single grip motion, hands are available that require more control information. Whether any one approach will be best is not obvious.

## PATTERN RECOGNITION FOR CONTROLLING MULTIPLE DEVICES

Improved hand-wrist control requires the integration of many new technologies. Pattern recognition is quite useful for controlling several motions sequentially, but so far, no 1 is offering a system for simultaneously controlling the three wrist motions or even simple one-DOF gripping. I believe the answer for myoelectric control lies in how signals are acquired. Researchers are still relying on skin-surface myoelectric sensors, which are plagued by motion artifact and electromagnetic interference. In addition, signal strength falls rapidly as the distance from the muscle fibers increases. Thus, even the best pattern-recognition schemes currently undersample information from deep muscles. Some in the field are working to collect information from individual muscles by using implanted electrode sensors [5]. Even if pure signals are collected from all the forearm muscles by adding implanted sensors, the information would not be sufficient for an amputee to simultaneously orient a prosthetic wrist and control a gripper. In the intact limb, the required motions are generated by muscles that act synergistically. For the most part, the muscles that cause the fingers to grip also flex the wrist. Thus, deciding what motion the user intends is impossible from sampling the activities of single muscles. Even with the addition of implanted sensors, pattern recognition will be needed to orient the hand while simultaneously using the fingers for gripping and manipulation. Will pattern recognition alone be enough to permit intuitive control? I believe that we also need a robust model of how the muscles of the forearm work together to control motion across multiple joints.

Meanwhile, the article by Simon et al. in this issue shows the extent to which pattern recognition can currently control wrist orientation in real time [6]. They tested the ability of subjects to reorient a hand-wrist on a computer screen using pattern recognition. Both a single motion and a 2-DOF motion were studied. Their study shows that applying pattern recognition to quickly accomplish simple tasks is still difficult.

Work on squeezing more information out of the myosignal continues apace, and the article by Simon et al. [6] and a more rigorous article by Nielsen et al. [2] show that, even with surface myoelectric inputs, simultaneous control of the two wrist functions and grip is becoming more practical.

Two other articles on myoelectric control in this issue should also be mentioned. In this issue, Corbett et al. ask whether the force produced by an isometric contraction is better for control than the myoelectric signal generated by the same or a similar contraction [7]. In their article in this issue, Scheme and Englehart have reviewed the work currently under way in pattern recognition [8]. With the introduction of powered wrists and multiarticulated hands, pattern recognition looks like the only way to extract intuitive control out of myoelectric signals. Since reports in this field are scattered in a host of specialized journals, this review identifies where to look and what is important.

## NONMYOELECTRIC SCHEMES FOR CONTROLLING JOINT MOTION

In this issue, Lipschutz et al. show that subjects have trouble using force-sensing resistors (FSRs), because these devices do not provide sufficient feedback and they give poor proportional control [9]. Two issues need to be addressed here. The first has to do with the way FSRs are traditionally used in prosthetics. Ideally, these devices would provide a signal proportional to the force on the FSR. I have carefully studied these devices, especially some recently introduced to the market. FSR is a misnomer—it is actually force-sensing conductor. Such a device is reasonably linear if conductance is measured versus pressure on the FSR. My laboratory at Liberating Technologies, Inc (LTI) (Holliston, Massachusetts) has recently developed a simple circuit that outputs a signal that is linear and proportional. It does this by outputting a value that is proportional to $1/R$, where $R$ is the resistance of the device. When FSRs were first introduced, such a circuit would have required a prohibitive amount of space. Now, two of these circuits can fit in a space equivalent to a U.S. penny. Better conditioning circuits will make FSRs much more useful. Proportional control is easy when the signal produced is truly proportional to force. LTI hopes to have a commercial version of this circuit on the market within a year.

The second issue with FSRs is that users do not move an appreciable distance as they activate the FSR, making sensing how much force is being produced difficult. This problem is easy to address. Each FSR should be covered with a resilient conical pad about 8 mm high. With the proper shape and resilience in the pad, a user can feel both the change in skin pressure and the increased contact area as the FSR is pushed. Combined with the conductance circuit above, an FSR will then produce a signal, giving the user good proportional control. This will be a marked improvement over present FSR control, which is little better than using an on-off switch.

## WHY ARE BODY-POWERED, CABLE-OPERATED DEVICES STILL IN USE?

When studying prosthetic control systems, one should always return to the question of why cable-operated, hook-type devices are still popular. Soldiers returning from Iraq and Afghanistan are eligible for any device that will assist them in their daily activities, work, and recreation. Yet after trying the most sophisticated powered devices, many transradial amputees choose a simple cable-operated split hook or a voluntary close hook-type device. Why? Two main reasons: speed and feedback. Yet another reason for choosing the simple hook is that once an object is secure in the hook, the user can forget it. Because the body's proprioception is brought into play, users can sense how open the hook is, even in the dark. Most powered devices, on the other hand, use myoelectric signals for control, and no positional information is gained from the generation of a myosignal. Some of the best “myo-users” get a feel for position by listening to the motors and sensing how long the device is taking to change position, which is no substitute for real proprioception.

## USING A CABLE TO POSITION A POWERED ELBOW OR A HAND/TERMINAL DEVICE

For the transhumeral (TH) amputee, cable operation can be challenging, because the cable must perform two functions. The elbow must be positioned and locked before the terminal device (TD) can be operated with the same cable. To solve this dilemma, researchers developed powered elbows in the 1970s. With these powered elbows, the muscles that formerly flexed and extended the elbow (biceps and triceps) were used to generate myoelectric signals to intuitively position the elbow. Thus, the elbow was myoelectrically controlled, while the TD was controlled with a cable. With the advent of powered hands, cable control of the TD became impossible. Users had no easy way to control the available hands with a cable. At first, the only sources of control were the two remaining muscles in the upper arm. Users were required to use a switch or a cocontraction to sequentially control first the elbow and then the hand. More recently, the elbows sold by Motion Control, Inc (Salt Lake City, Utah), and LTI have been offered with positional servo control using a cable-activated linear transducer to control elbow position. The linear potentiometer within the transducer is pulled by the cable and typically moves about 12 mm with an adjustable-force spring to return the unit to its zero position as cable tension is reduced. The LTI unit can be set to move either 12 or 25 mm. Interestingly, almost all fittings use the smaller travel. How important is proprioception here? I believe that the real appeal of this control scheme is twofold. First, it separates control of the TD from the elbow, and second, it allows the user to preposition the elbow using a timed sleep mode—when the cable is held in a fixed position, the elbow position circuit goes to sleep. The cable can then be released until a new position is needed. While this strategy is popular, it actually makes minimal use of proprioception. Meanwhile, the remaining arm muscles, biceps, and triceps are used for myoelectric control of the TD. Using these muscles for TD control is backward. Remember that before powered hands were made available, powered elbows were fitted with cable-operated hooks. Persons using this scheme could flex and extend the elbow while simultaneously opening and closing the TD, thus passing the Glimscher test for simultaneous control of both devices. (Dr. Melvin Glimscher laid out the requirements for the first powered elbow and recruited the teams that made LTI’s original Boston Arm possible.) A cable-operated powered TD would allow a return to the more intuitive biceps-triceps control of the elbow.

Can one use a cable to control a powered hand? The answer is “Yes, but . . . .” Until recently, no commercial hands had been introduced with positional feedback. Several years ago, I modified a simple Bock hand without electronics by adding a potentiometer that responded to hand position. Using the control circuits built into the LTI elbow, I then attached a linear transducer to position the hand. The circuit was configured to open the hand as the cable pulled the transducer. Release of the cable let the hand close until the user could hold the cable in a fixed position to engage the sleep circuit. Alternatively, the rise in motor current as the hand closed on an object would stop the motor and engage the sleep circuit. This project was never fitted to a patient but remains a good proof of concept. The project was set aside for a time when hands might become available with built-in positional feedback. The time has come. I challenge my fellow developers to work out the control algorithms that are needed to operate the new multiarticulated hands by using a simple cable-actuated linear potentiometer.

## USING SHOULDER MOTION FOR CONTROL

In 1994, I studied shoulder motion with the idea that it would provide a good control input [10], and later I expanded on this idea [11]. The essential observation concerning shoulder motion discussed in both of these studies is that the acromion is joined near the center of the chest at the sternoclavicular joint and that the other end of the clavicle is constrained to move on the surface of a sphere. Most high-level arm amputees can move the acromion up and down (shoulder elevation and depression) and forward and backward (shoulder protraction and retraction). Because of the constraint, these two motions are completely independent and an amputee sensing them as he or she moves the shoulder can produce two independent control signals. While the study was extensive, it was backed up by little hard data (one subject) [11]. Two articles in this issue make up for this shortcoming. Lipschutz et al. have used a joystick mounted medially to measure the motion of a shoulder cap covering the acromion [9]. Five subjects validated that this simple scheme could give good control of two DOFs. In their article in this issue, Losier et al. used a joystick mounted external to their subjects to study the feasibility of end-point control as opposed to the traditional velocity and direction control [12]. They also compared the effectiveness of end-point control with all myoelectric control assisted by pattern recognition. The myoelectric signals were collected from the muscles of the shoulder, including those that would control arm motion in an intact subject. Joystick control with the concomitant feedback was superior. These two articles have implications for the design of shoulder socket interfaces. Presently, several designs are used often enough to be called standard. They solve the problems of comfort and suspension rather well, but few studies report on optimizing these interfaces for implementing the type of control Lipschutz et al. and Losier et al. discuss [9,12]. They both require recording the motion of the acromion with respect to the core anatomy, and both detect motion with the use of joysticks. The shoulder cap studied in a clinical setting by Lipschutz et al. may be a promising addition for isolating shoulder tip motion. Further research is needed to optimize the rest of the interface to make the cap work well with it. Caps of varying sizes and shapes must be studied on more patients. How many strips of elastic are best for positioning the cap and where should they be placed? Means for detecting motion other than a joystick also need exploration. And finally, even with the cap, more control sites are needed. Thus, the ideal interface also locates suitable stable contacts for collecting myoelectric signals from muscles not involved in moving the tip of the shoulder.

## SHOULD RESEARCHERS REVISIT EXTENDED PHYSIOLOGICAL PROPRIOCEPTION?

Both Winter and Carlson and Doubler and Childress [13–14] have reported on schemes for controlling a Boston Arm using a variation of Simpson's extended physiological proprioception (EPP) [15]. Both studies used a shoulder-operated cable to apply tension to a forearm-mounted force transducer after the cable had been passed around a pulley on the axis of the powered elbow. The control system is set so that a reasonable cable tension generates an equilibrium signal with the forearm and gripper at about 90° of elbow flexion. More tension flexes the elbow and less extends it. Very little force is required to flex the elbow when the user is compensating for the weight of the forearm and gripper. When a greater load is applied at the end of the forearm, more force is required to cause motion, giving the user a feel for the size of the load. This scheme gives no extension feedback. My experience with amputees suggests that the set-it-and-forget-it circuit with a linear transducer discussed earlier should be added to this control scheme to conserve power and free the user from thinking about the elbow when it is not needed. Two decades ago when I tried to adapt this scheme to work with the Boston Elbow, the use of a cable passing around the elbow axis made this control too complex and difficult. Now that programming microprocessors so that all information is passed as electrical signals is relatively easy, it is time to revisit this approach.

## SOCKET INTERFACES THAT IMPROVE CONTROL FOR THE SHORT TRANSHUMERAL AMPUTEE

In this issue, Alley et al. discuss a new approach to stabilizing sockets with respect to the underlying bone [16]. Socket stability is a key element in controlling the location of the TD. For instance, in the ideal TH prosthesis, the TD would move with the humerus with no lost motion. Alley et al. report on work spread over several years. During the preparation of the article, a number of short TH amputees have replaced their traditional sockets with the new design. These users are able to handle increased weight at the end of the forearm, even when the entire arm is held at 90° of flexion. In addition, they are able to reach overhead, most of them for the first time. These improvements come without any additional surgery. A well-fitting TH socket must also prevent inadvertent rotation around the long axis, and these sockets follow the long-established practice of the use of two wings to apply pressure over the deltopectoral groove and at a position on the back. Unfortunately, these stabilizers do not allow the user to employ the remaining rotation of the humerus for control of internal-external rotation.

Improving the design of socket interfaces has also received attention from the U.S. Department of Defense and its research arm, the Defense Advanced Research Projects Agency (DARPA). Two projects to develop improved arm prostheses have begun to spin off interesting results. In this issue, Resnik reports on the creation of a protocol for studying prosthetic devices during the development cycle [17]. This protocol is being used in a joint study with the U.S. Department of Veterans Affairs and the DEKA Research and Development Corporation (Manchester, New Hampshire), one of the development contractors, to further improve a prototype arm produced under the DARPA project. Resnik will report on this study in *JRRD* when it is complete.

## THE INTERNAL-EXTERNAL ROTATION CHALLENGE

Most TH amputees can rotate the humerus through a full range of motion, but in the past coupling this rotation to a socket had never been possible. For some users, this dilemma can now be addressed by using osseointegration [18], which permits direct attachment of the prosthesis to the humerus. This procedure requires several surgical procedures with many months of healing in between and a lifelong commitment to careful personal hygiene. Only a limited number of persons will elect this route. Another approach is the work of Witsø et al., a simple T-shaped titanium implant inserted into the end of the humerus to give the TH amputee artificial epicondyles, which improve suspension and directly couple the user to the prosthesis, thus returning control of internal rotation [19]. The small number of patients offered this implant found that it needed further refinement if it were to fully suspend the weight of a prosthesis. This finding need not be considered failure. Such patients usually require harnessing to achieve independent control of the TD and the elbow. With most of the suspension load removed by the harness, artificial epicondyles can return full bodily control of internal rotation. Unfortunately, this work seems to be on hold since initial positive reports suggesting that the problems uncovered during the early fittings could be solved by further research. Other solutions to the rotation problem are the friction turntable that has been in use for over half a century, as well as friction turntables combined with locking positions every 30°. More recently, the projects funded by DARPA have added a powered humeral rotator. However, the use of power is not the same as the control of power. Many years ago, I proposed placing a small magnet crosswise in the end of the humerus so that rotation could be sensed directly. Such a sensor would permit intuitive control of this rotation. Research at Northwestern University (Chicago, Illinois) has now shown that use of this sensor is feasible [20], and I challenge researchers to put this work into practice.

## VALIDATED TRAINING—A MISSING INGREDIENT IN THE RESEARCH REPORTED

When reviewing a single article, one often misses subtle deficiencies in the research protocol. As the editor of this issue, I have had the opportunity to step back and ask how the overall quality of the research might be improved. Because upper-limb amputations are rare, most researchers use nondisabled subjects for their studies and they also assume that valid measurements can be collected during a single session of training followed by data collection. No coach would expect to produce a superior athlete with a single, albeit long, training session. Rather, one new skill at a time is introduced and then followed by time away from the task. Here, sleep is particularly important for task consolidation. Even a little time off will improve performance. When Farry studied the ability of children with congenital and traumatic amputations to control a computer-generated image of a hand-wrist system, she worked with her subjects both early in the day and then after a lunch break [1]. Remarkably, during the break, many of her subjects with congenital amputations developed a *phantom hand*. No one has previously reported on the development of phantom hands in congenital amputees. This research has not been repeated by others, but it has implications for all of us. I believe that before formal data collection begins, preliminary experiments should be conducted to test how much training is required to reach a level where no further improvement occurs, particularly when one is working with amputees. When I have worked with amputees who are many months postsurgery, I have found that acquisition of a myoelectric signal is more like training someone to wiggle their ears than it is eliciting a response to a verbal command. Thus, that at least one of the articles in this issue notes that amputee subjects did not seem to learn as well as nondisabled subjects is no surprise. Because no standard exists for validating the adequacy of training, the reader does not know how well the amputee subjects might have performed if they were trained differently or simply more. I hope that the occupational therapists who work with amputees will help the research community develop a validation-of-training protocol. Note that I am not recommending that amputee subjects be used exclusively. In a typical research setting, student subjects are easy and inexpensive to recruit. Nonetheless, studies will be most valid when some amputees are included and their training is proven adequate.

## FUTURE CHALLENGES

### Speech Recognition to Permit Task-Oriented Control

Anyone who has used Dragon speech recognition software (Nuance Communications, Inc; Burlington, Massachusetts) [13] knows that one can control a computer or other device in a number of different ways, simply by speaking. Skilled users of this software can bury control clues into their speaking. Then they can carry on a conversation while simultaneously carrying out low-level control tasks. With this in mind, I challenge those working on pattern recognition and other control systems to use voice input for changing control modes in ways that are specific to the tasks being carried out. Consider, for instance, the end-point control discussed by Losier et al. in this issue [12]. With it, a subject using only shoulder motion and contraction of a single muscle can control the location of the end of the forearm in space intuitively. Missing from this scheme is an easy way to shift this 3-DOF control to the orientation of the wrist or the closing of the TD. The ability to alter control on the fly would be of particular benefit when a user is eating and drinking. Giving a vocal clue to the prosthesis to shift to drinking mode should be easy; this would keep a glass held in an artificial hand in the same orientation with respect to the vertical while bringing it to the mouth. The ideal software would allow the user to preprogram the system such that the glass would tip appropriately for drinking when the elbow angle reached a suitable value. Just about anyone can learn to produce a dozen or so non-semantic speech clues to initiate shifts in control. Compare this to the usual contortions required of patients to produce only one or two shifts in control. Cocontraction requires a lot of mental effort, and producing a rapid versus a slow cocontraction requires even more. Clearly, this new control source needs immediate investigation.

### Eye Tracking for Endpoint Control

Considerable work has been done in other fields to use eye tracking for control. The data collection hardware usually targets military applications where placing additional sensors on a helmet is little trouble. To be acceptable to amputees, the sensors need to be small enough to mount inconspicuously on a pair of glasses. The relatively small number of people with amputations is not sufficient to justify this research; but if the computer game industry were to find this input useful, amputees could benefit. Consider how easy it would be to position the wrist in space with eye tracking. The user would initiate tracking by focusing on a target on the wrist for a settable interval and terminate tracking with a blink. The inputs freed up could then be used to increase the control of the TD and wrist.

### Audio Feedback

Today many individuals appear in public wearing miniature earphones and other listening devices. Such inputs no longer imply that the user is disabled. By superimposing audio feedback signals on the sounds already reaching the ear, I believe a surprising amount of information could be conveyed. While work is also being conducted to supply information directly to task-specific nerves, it will likely be a long time before this technology can be applied, especially to persons who do not wish to undergo any additional surgeries. Audio feedback would also be simpler to implement than various skin-input schemes, such as tactors that stimulate by vibrating or changing pressure on the skin. For audio feedback, little special-purpose hardware is required. Low-cost handheld computers are now sold in vast quantities. Writing an application to create an appropriate audio signal from feedback data provided by a prosthesis should be relatively easy. The application would then create an audio signal that would be transferred to an ear bud or similar receiver using a standard wireless protocol. Data would also be transferred via a standard wireless protocol. The ears have a special advantage as inputs. They already differentiate between signals coming from the left or right. Perhaps the apparent left-right motion of a subtle background frequency could report on elbow flexion angle while a second frequency reported on changes in another variable. Research on this mode of feedback should be easier to fund than other prosthetics-only research, because many possible applications exist for nondisabled users working on complex tasks, for the computer game industry, or for military applications.

## RESEARCH YOU MAY NOT KNOW ABOUT

A number of studies are not well known but should be. One example is an important article by Farry et al., presented at the Myoelectric Controls (MEC) Symposium in 1999 (Fredericton, Canada), reporting on magnetic resonance imaging studies of amputee forearms [22]. For almost four decades, the University of New Brunswick (UNB) (New Brunswick, Canada) has sponsored the MEC. This symposium has changed shape over the years and is now the most important venue for presenting new ideas and research on the control of upper-limb prostheses and much more. The articles in its proceedings are not formally peer-reviewed, but they are vetted ahead of time by a committee of experts. At this time, the Biomedical Engineering Institute at UNB is working to make these proceedings available online.*

Typically, new ideas are introduced at MEC years before they appear in formal articles or before they lead to improved devices for upper-limb amputees.

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*For an update on progress toward making the MEC proceedings available online, email pkyberd@unb.ca.

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