Comparative Analysis of Microprocessors in Upper Limb Prosthetics

Christopher Lake, CPO, FAAOP, and John M. Miguelez, CP, FAAOP

ABSTRACT

The recent emergence of microprocessor-based prosthetic control for the individual with upper limb deficiency has expanded the spectrum of treatment options and inclusion criteria for this patient population. Microprocessors can accept a wide variety of input devices and ranges to enhance an individual's prosthetic function and to allow myoelectric control options for individuals who, although strongly indicated for electric prosthesis, were not candidates for such prosthetic management secondary to limited control strategies and myo-signal strength of available systems. Additionally, myoelectric control parameters can be adjusted to optimize function while retaining the flexibility to individualize each prosthesis. With multiple processors available, it is difficult to identify the appropriate component for a particular patient. Variables that should be examined include the amount of clearance available for microprocessor integration, weight of the microprocessor and appropriate power supply, compatibility of existing components, and patient requirement for such technology. Several microprocessors, including the Otto Bock DMC/Sensor Hand, ProControl II, and Programmable VariGrip III, were analyzed. This comparison of the microprocessors provides valuable feedback for prosthetists as they weigh the advantages and disadvantages of each system to optimize both functional and cosmetic requirements for a patient. (*J Prosthet Orthot.* 2003;15:48–63.)

KEY INDEXING TERMS: upper limb prosthetics, upper limb deficiency, myoelectric control, upper extremity amputee, microprocessor.

HISTORICAL PERSPECTIVE

Many important achievements are apparent as one examines the evolution of electronic upper limb prostheses during the last 30 to 40 years. The evolution of commercially available electronic upper extremity prostheses can be summarized into three distinct generations. First generation electronics, often referred to as digital systems, used an on and off control scheme to actuate electronic terminal devices, wrist rotators, and elbows. These digital systems exhibited a single speed or single rate type of actuation of prosthetic terminal devices. During the first generation there was limited sophistication of input devices. At that time, input devices consisted of myo-electrodes and various switch technology often mounted in the prosthetic interface or attached to a control harness (Figure 1).

Delineation between first and second generation was made with the introduction of the Utah Arm (Motion Control, Salt Lake City, UT) and later the ProControl I (Motion Control) prosthetic controller (Figure 2). Both systems allowed for large-scale threshold manipulation, greater gains, and muscle EMG signal amplification, as well as adjustment of muscle contraction rate, in an attempt to minimize the effort required in first generation co-contraction type switching. These systems lowered the microvolt requirement (by lowering the muscle thresholds) for terminal device, wrist, or elbow control, allowing more individuals with upper limb deficiency to take advantage of myo-electric prosthetic technology. Most importantly, these systems introduced proportional control in a reliable electronics package.

Although more sophisticated than the first generation, second generation electronics exhibited challenges that affected the ability of the prosthetist to provide expeditious prosthetic management and interchangeability. Through the second generation, switch-activated, single-site or dual-site myo-electric control systems required different electronic packages. If, during the rehabilitation of the patient, it was noted that dual-site control was too difficult and single site would be more appropriate, a new electronics package would need to be installed into the prosthesis, creating additional expense and fabrication time at the point of rehabilitation, where timing and expeditious prosthetic function is so very critical.

The third and most current generation of prosthetic electronics incorporates programmable microprocessors. Third generation electronics are delineated by the acceptance of proportional control as the standard. Microprocessors of the third generation allow an infinite range of adjustment of

CHRISTOPHER LAKE, CPO, FAAOP, is Southwest Clinical Director of Advanced Arm Dynamics of Texas, Center of Excellence, Dallas, Texas.

JOHN M. MIGUELEZ, CP, FAAOP, is President and Senior Clinical Director, Advanced Arm Dynamics, Inc., Rolling Hills Estates, California.

Correspondence to: Christopher Lake, CPO, FAAOP, Advanced Arm Dynamics of Texas, Center of Excellence, 1451 Empire Central, Suite 700, Dallas, Texas 75247; e–mail: JCLAKE@airmail.net

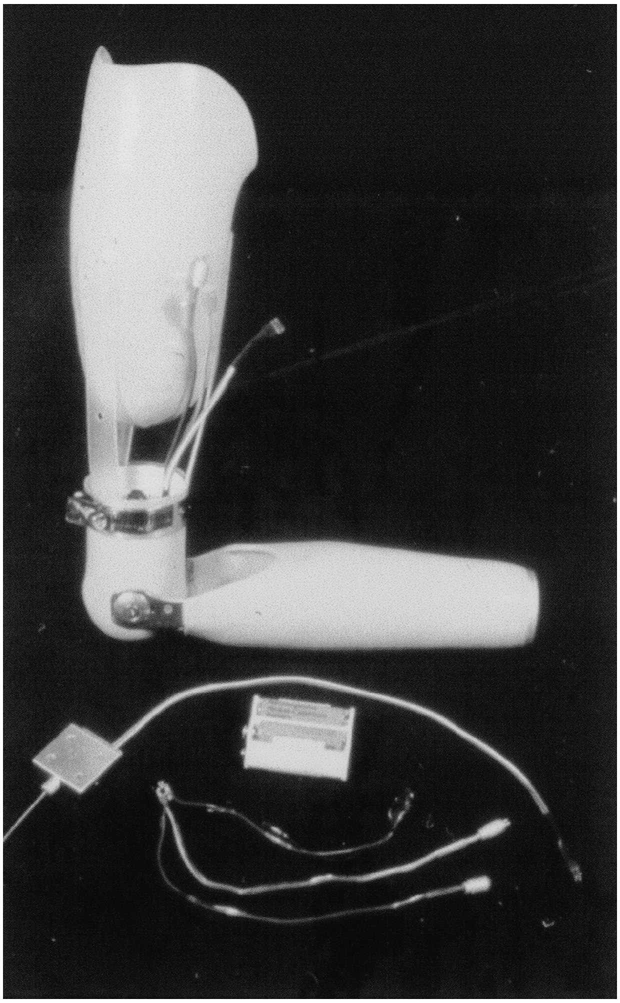

Figure 1. Prosthesis utilizing switch control.

myo-electric characteristics for the enhancement and simplification of prosthetic control.

BENEFITS OF MICROPROCESSOR USE

Microprocessor use in upper limb prosthetics benefits both the patient and funding source. One should appreciate that these benefits are inclusive to the microprocessors discussed, but do not take into account the system-specific benefits that will be discussed below. As microprocessor technology progresses, benefits are likely to increase and become enhanced.

Microprocessor use provides the ability to modify control options and adjust input characteristics quickly throughout all stages of prosthetic management without purchasing or exchanging components. This important aspect reduces third party cost by providing multiple control options in one electronics package. Furthermore, it allows for expeditious provision of prosthetic management facilitating return to function in agreement with Malone's guidelines for optimal return to function.[1]

According to Malone's study,[1] individuals fit with a prosthesis within 30 days of amputation exhibited a 93% rehab success rate with a 100% return to work rate within 4 months of injury. Those fit beyond the 30-day window exhibited a 42% rehab success rate with a 15% return to work rate within 6 to 24 months. Considering an individual with a recent upper limb amputation, the Otto Bock SensorHand (Otto Bock, Minneapolis, MN) provides the microprocessor example. The patient can be managed first (early fitting stage) by using a switch control scheme for opening of the hand with proportional closing addressed through sophisticated algorithms and sensor technology. As the patient's ability increases, the control scheme and functionality can be addressed with varying input and control scheme adjustments (Figure 3). This scenario should be considered in respect to socket replacements and associated procedures that will be necessary as the residuum matures. Without the use of a microprocessor based system, the effective treatment (respecting the Malone findings) of this patient would have required one complete prosthetic system for early prosthetic management (switch controlled hand—digital), one for preparatory prosthetic management (single site hand—digital), and possibly a third for definitive prosthetic management (dual site hand—proportional). With the provision of these different prosthetic component packages, third party expense would likely be high and patient functional development would become interrupted in the shadow of multiple insurance authorizations.

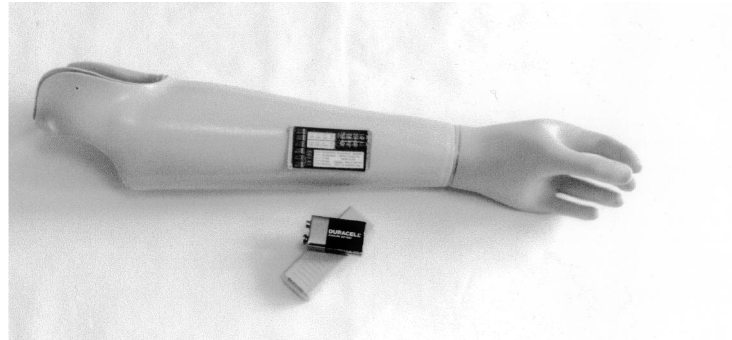

Figure 2. The ProControl I Controller.

The use of microprocessors allows more complex filtering of the EMG signal resulting in enhanced terminal device responsiveness. Secondarily, microprocessors provide ease in changing control thresholds and sensitivity of the prosthesis as the user's strength and ability evolves. Associated with this benefit is the added feature of real-time signal analysis.

The microprocessor-based example of this benefit is made in respect to the ProControl II system. For example, as the patient's muscle strength increases, it is likely that one muscle will become stronger than the other. This muscle imbalance leads to difficulty as learned muscle signal patterns and contraction strengths no longer provide consistent reliable functional outputs. If muscle imbalance issues are allowed to progress, patient frustration will develop, leading to reduced prosthesis use and possible rejection. Furthermore, the muscle imbalance may lead to loss of electrode contact as hyper-

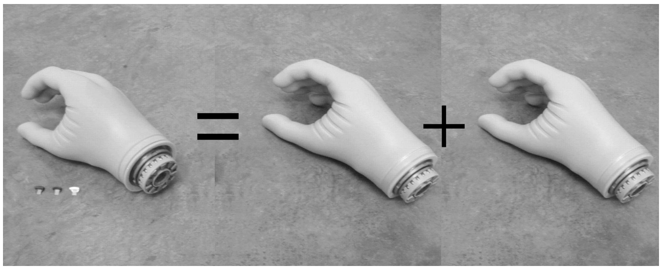

Figure 3. Otto Bock SensorHand utilizing 3 coding plugs for different stages of early, intermediate, and definitive prosthetic management, equates to utilization of a switch-controlled hand during early prosthetic care, then a digital (single or dual site) hand, and later a DMC hand.

trophied and atrophied muscles cause anatomical socket stabilization loss during muscle contraction. Real-time myo-signal analysis facilitates prosthesis adjustment by allowing the practitioner to observe myo-signal characteristics during functional activities involving full range of motion, positioning, and external forces. Without microprocessor use, this analysis and manipulation of input characteristics would not be possible, adversely affecting the patient's ability to maintain reliable prosthetic function and likely leading to lengthy troubleshooting. Clinical experience provides the familiar patient response of "the prosthesis functioned well for 3–6 months . . . then stopped working properly." This statement is sometimes heard from the patient who decided to discontinue electric prosthesis use secondary to malfunction issues. Clinical experience indicates that this issue is one of follow-up challenges exhibited in non-microprocessor systems and with non-comprehensive upper extremity prosthetic management. When muscle characteristics are monitored and recorded, trends are noticed and adjustment can be made before function is compromised and patient frustration develops (Figure 4).

Microprocessor-based technology exhibits the ability to document and store patient information. The microprocessor-based example of this benefit is made in respect to the VariGrip III (Liberating Technologies, Inc., Holliston, MA) microprocessor system (Figure 5). Patient information, electronic settings, input characteristics, and patient usage patterns can be recorded and recalled as necessary. This allows for long-term treatment goals to be monitored. For example, the practitioner can determine progressive functional use by reviewing muscle strength adjustment changes and usage data. The increase in prosthesis use can be appreciated. Most important, a decline in prosthetic use can be noted signaling the initiation of prosthetic protocols directed at determining the cause of such a decline. These protocols often reveal the need for further therapeutic intervention, input or myo-signal manipulation, as well as psychosocial consideration.

Microprocessors utilize algorithms to inherently adjust to various situations unknown to the patient, "reducing the mental effort" necessary to function with an electric prosthesis (Hans Dietal, PhD, Otto Bock, personal communication).

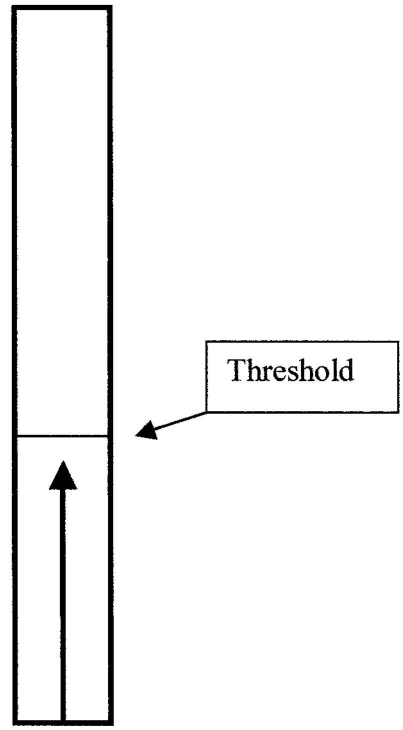

Figure 4. Myo-signal should indicate a fluid representation in the interface software. Sudden jumps or erratic motions may indicate electrode lift. Early observance allows expeditious handling of this issue.

Otto Bock's closed-loop control algorithms provide the best example of this benefit. Closed-loop control provides a direct relationship between muscle contraction and hand speed as well as a direct relationship between muscle contraction and grip force. Small contractions elicit fine control with light grip forces and larger contractions allow for faster terminal device speeds and increased grip force. Most important, terminal device operations are predictable for the patient. This is in contrast to the observation that non-Otto Bock systems utilize a time-based algorithm for grip force, allowing excessive grip forces to be exhibited with small muscle contractions. For example, a person provides a muscle contraction 3–5 microvolts over the threshold level. A closed-loop system utilizing muscle signal strength for grip and speed characteristics would generate a small amount of grip (possibly only a few of pounds of pinch force) moving at a slow speed. The time-based microprocessor system would exhibit similar speed characteristics but grip would increase to the maximum limit (approximately 22 pounds) as long as the muscle remained contracted over the threshold level. While the time-based system may provide benefit to the individual who can not generate sufficient myo-signal by allowing grip force to be increased by length of contraction, it requires visual observation of grip to predict grip forces. In contrast, the closed-loop system is predictable because the same level of signal will always equal the same amount of grip and speed characteristics. The closed-loop system is challenged by requiring more muscle strength to exhibit more grip force.

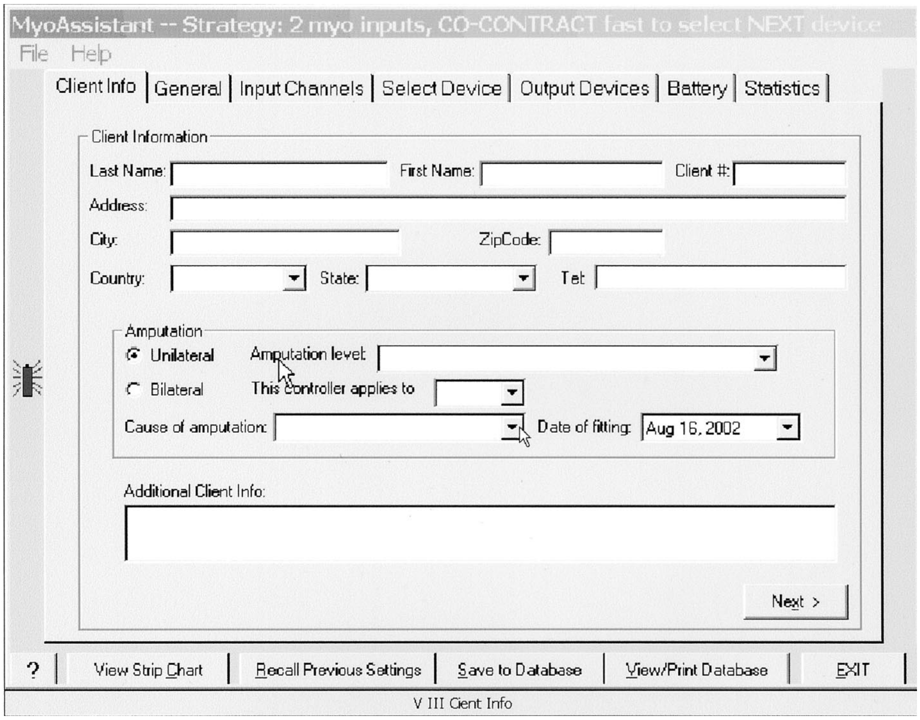

Figure 5. Programmable VariGrip III client information tab.

Another benefit of microprocessor use is the ability to incorporate predefined programs that monitor and respond to prosthetic functioning. These "behind the scenes" algorithms enhance patient function, reduce concentration, and adhere to the principle that "prosthetic use and function should not bother the patient" (Hans Dietal, PhD, Otto Bock, personal communication). Examples of predefined microprocessor functions include grasp stabilization in the Otto Bock SensorHand, auto calibrating algorithms found in the ProControl II, and usage monitoring in the VariGrip III processor.

These benefits are enhanced by consistent follow-up and patient commitment to a comprehensive rehabilitation plan that includes occupational and psychological therapy. While many related topics are discussed in the literature, there is a void in the literature when one investigates commercially available microprocessor technology.[2–10] This article is based on discussions with individual manufacturers (Hans Dietl, PhD, Otto Bock–Austria [Wien, Austria] and Pat Prigge, CP, Otto Bock–USA [Minneapolis, MN]; Harold Sears, PhD, Motion Control [Salt Lake City, UT]; William Hansen, MS, and T. Wally Williams, MS, Liberating Technologies [Holliston, MA]) as well as comparative microprocessor analysis performed by the authors.[11,12]

MICROPROCESSOR AUGMENTATION

Before one enters the discussion of different microprocessors, it is important to appreciate what devices (output) are influenced by microprocessors. Currently, microprocessors control terminal devices, wrist and elbow functions, as well as more esoteric options such as shoulder joint locking and unlocking, remote on and off, and sensory feedback. Furthermore, microprocessors illustrate an augmentation to current types of control, not necessarily a type of stand-alone control. The microprocessor delineates, filters, and enhances input characteristics to produce the desired output, optimizing prosthetic function and increased ease of use (Figure 6).

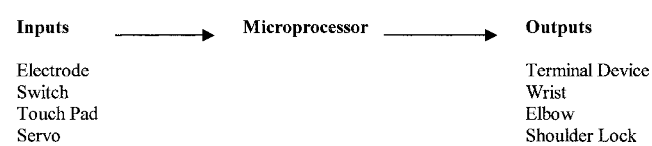

Figure 6. Function of the microprocessor.

Microprocessor control of terminal devices can be further divided into two classifications: those that have intrinsic or internal processors and those that use extrinsic processors (Figure 7). Intrinsic processors have the advantage of reducing the amount of space distal to the interface and proximal to the terminal device to achieve a contralateral limb length match. Intrinsic processors are appropriate for individuals with longer residual limbs or those concerned with the cosmetic contours of the prosthesis. Intrinsic processors—in contrast to extrinsic processors control only one device per processor, necessitating the use of multiple processors for multiple devices (i.e. hand, griefer, and wrist usage) increasing costs accordingly. Intrinsic microprocessors exhibit an inherent advantage, as these microprocessors are fine tuned to one specific device. For example, the functional characteristics of the Otto Bock DMC Griefer, SensorHand, and DMC

A B

Figure 7. A: Motion Control Hand—controlled by extrinsic processor; B: Otto Bock SensorHand—controlled by intrinsic processor. (Images courtesy of both manufacturers.)

Transcarpal hand demand different preset microprocessor settings.

Extrinsic processors, on the other hand, are located proximal to the terminal device. These types of processors have the advantage of extra protection about the prosthetic interface, ease of replacement, and the ability to control functions other than the prosthetic terminal device. It is important to note that not all microprocessors are compatible with commercially available terminal devices and that referencing both microprocessor and terminal device manufacturers' recommendations is necessary to avoid compromising warranty guidelines. Often the challenging aspect of third generation electronics is understanding system compatibility, reliability, and appropriate control inputs. Furthermore, although a terminal device is considered compatible with an extrinsic microprocessor, it may not necessarily provide optimal function with that system.

Microprocessor control of the wrist allows for several control schemes to be incorporated to allow ease of switching between the terminal device and the wrist (Figure 8). One of the most common types of switching is represented by the co-contraction or contraction and relaxation of two separate muscle groups rapidly and simultaneously. Because of myo-signal differences from muscle imbalances secondary to amputation surgery or general conditioning of the prosthetic user, proper co-contraction can be difficult for the amputee. Use of a microprocessor allows the prosthetist to manipulate muscle thresholds and/or rates to provide reliable co-contraction switching. Muscle thresholds represent the signal level required to initiate function. Myo-signals below the threshold elicit no function, and myo-signals above the threshold exhibit function proportional to the amount of microvolts above the threshold. Muscle rates represent the speed at which the myo-signal crosses the threshold. Manipulation of both of these characteristics allows the prosthetist to equalize muscle imbalances or weaknesses facilitating co-contraction switching while preventing inadvertent switching.

Wrist function, in particular switching from terminal device to wrist, can sometimes be frustrating secondary to accidental switching caused by any number of reasons. Wrist function can be further refined through the use of relax timers, switch windows, and other switching modalities such as the complex switch-over. Relax timers require that the patient relax for an adjustable amount of time before a co-contraction is recognized. For example, when a patient utilizes the terminal device in a quick manner, co-contraction is likely. This often leads to unintentional switching, leading to patient frustration. The relax timer is set so that only co-contractions that follow a period of relaxation (no muscle contraction) above the threshold are recognized, leading to more predictable function.

Switch window adjustments, as found in the ProControl II system, allow the prosthetist to adjust the tolerance between the timing of the muscles crossing the threshold level during a co-contraction. The larger the window, the more time allowed, the easier it is to utilize co-contraction switching. A familiar analogy is that of throwing a ball through a tire, the larger the tire (or the window), the easier it should be to successfully throw the ball through the tire.

Finally, complex co-contraction, as found in the Otto Bock systems, utilizes a co-contraction followed by a shorter contraction of one of the two muscles to initiate switching. Unique to the Otto Bock system is the predefined wrist activation algorithm that allows for four-channel and co-contraction control switching.

Microprocessor control of elbows. A notable change between second generation and third generation electronic elbows is the latter's ability to accept more input options and allow simultaneous control of elbow and terminal device. Microprocessor control for electronic elbows is at the developmental stage. The Boston III (Liberating Technologies), ErgoArm (Otto Bock) (microprocessor control of unlocking), and Vasi-Pediatric (Variety Ability Systems Inc., Toronto, Ontario) elbows are the first electronic elbows to utilize a microprocessor for on-board adjustments. A more popular type of elbow application includes the use of an internal or external microprocessor in a hybrid prosthesis, most commonly seen with the Otto Bock ErgoArm (with easy plug application) (Figure 9).

Microprocessor control at the shoulder is limited to joint locking and unlocking, utilizing several different input options (Figure 10). Currently, commercially available electronically powered positioning shoulder units do not exist.

TYPES OF CONTROL: INPUT CHARACTERISTICS

Electric upper extremity prosthetics use three basic types of control schemes from which multiple combinations or strategies can be derived:

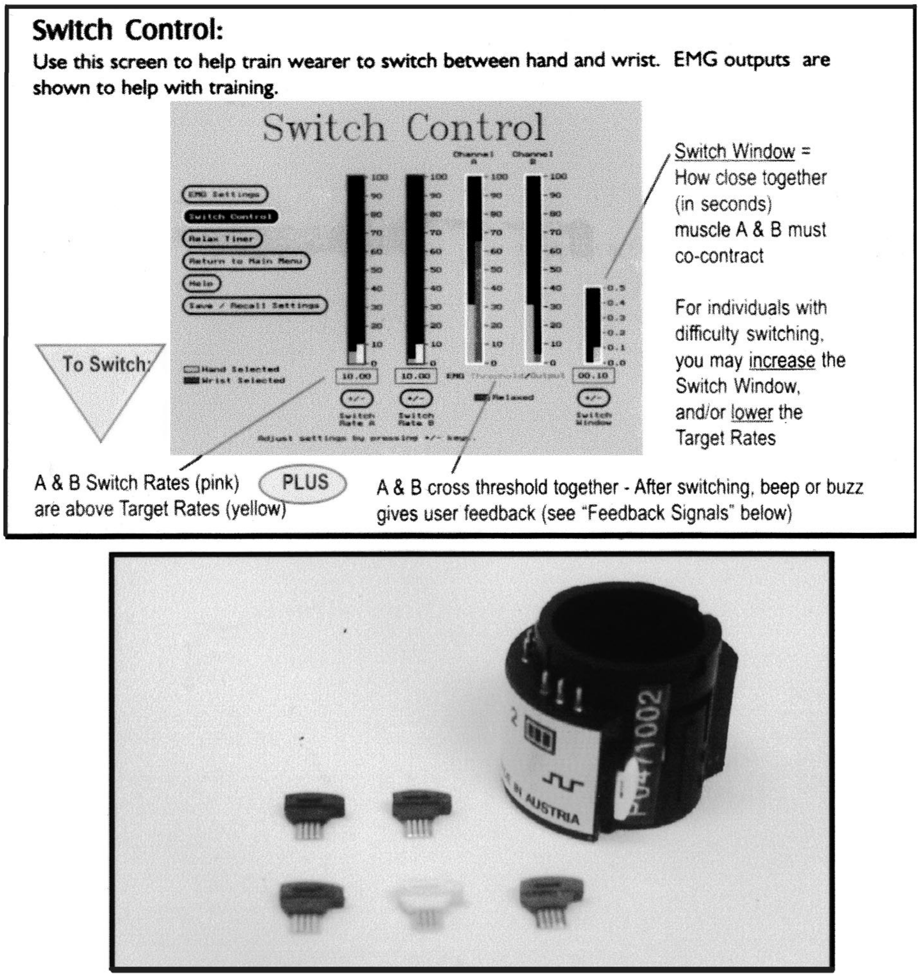

Figure 8. Pro Control II switch control window (top) can be accessed with interface laptop use for adjustment of co-contraction switching between wrist and hand functions in contrast to the Otto Bock four-channel processor (bottom), which requires removal of the wrist to change control modes. (Top illustration courtesy of Motion Control, Inc.)

MYOELECTRIC

Single Site

The single site system consists of a single electrode that utilizes the rate of the muscle contraction to control opening and closing of the terminal device or pronation and supination of the wrist. An example of this would be the utilization of slow contractions at low EMG and fast contractions resulting in higher EMG reading to control separate terminal device function. Additionally, single site electrode systems with voluntary opening and automatic closing are available (sometimes referred to as "cookie crushers"). The Otto Bock SensorHand allows the use of voluntary opening utilizing one EMG site with proportional closing through Auto-Grasp technology.

Dual Site

The dual site uses two electrodes to independently control a terminal device, electronic wrist rotator, or elbow. An example of this control scheme: one muscle/electrode controls opening of the terminal device while the second muscle/electrode controls closing of the terminal device. When an individual contracts one muscle, the opposite or opposing muscle may elicit a myo-signal as well. This may become problematic if the antagonistic muscle elicits a signal close to the same microvoltage of the primary muscle. This is seen in microprocessor systems, such as the ProControl II, that utilize myo-signal differentiation (the difference between the two muscles) to calculate proportionality. Systems with the Otto Bock DMC+ microprocessor features operate on a first-come, first-served basis. The VariGrip III system allows the patient to evaluate both strategies through microprocessor adjustment by the prosthetist. Patient muscle characteristics and functional needs may dictate the use of one microprocessor over the others.

If a person exhibits inadvertent antagonist muscle activity with the A muscle presenting as a 50 mV signal and the B muscle presenting with a 40 mV signal, their proportionality of myo-signal would be only 10 mV in the differentiation strategy. In the first-come, first-served strategy their proportionality of myo-signal would be equal to the difference above the threshold, most likely 30 mV.

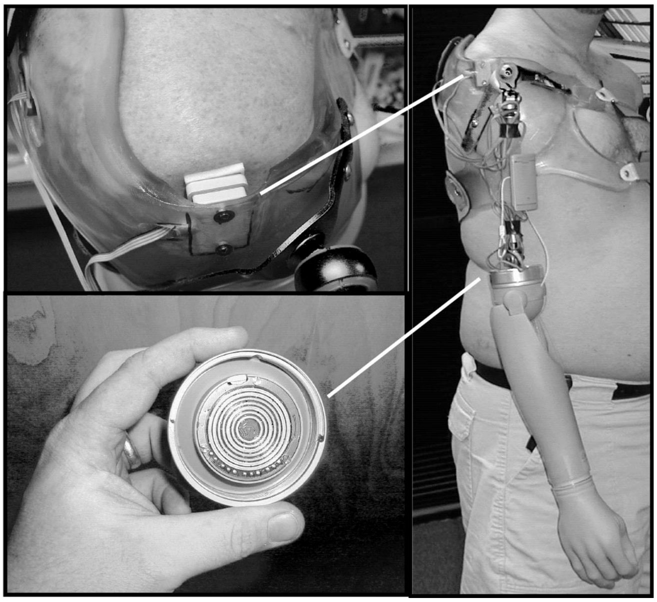

Figure 9. Hybrid application utilizing Otto Bock ErgoArm with electric unlock.

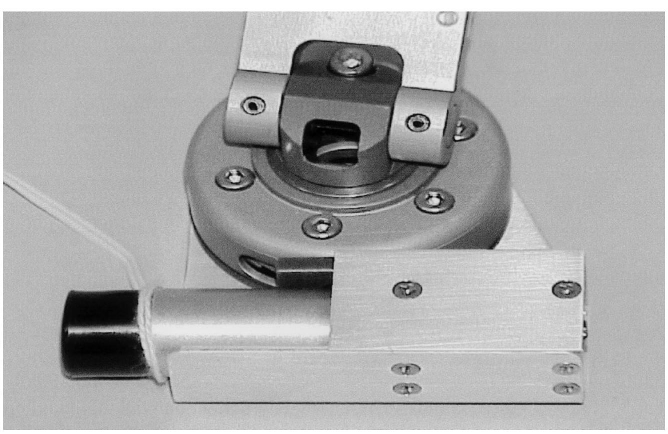

Figure 10. Electronic shoulder lock from Liberating Technology used in conjunction with the Collier (Liberating Technologies, Inc.) shoulder joint.

SWITCH

There are many types of switches. Some are activated by pulling a cable, while others are activated by depressing a lever or button. Some switches have multiple functions determined by the position of the switch. Switches do not have proportionality or proportional control.

SERVOS AND FORCE SENSING RESISTORS

Servo actuators interpret excursion and/or force and translate this input into a proportional output. As a result, feedback enhances proprioception as illustrated in the direct force or excursion relationship to elbow, wrist, or terminal device function. Proprioceptive feedback is similar in the servos and force sensing resistor (FSR), which is further discussed below.

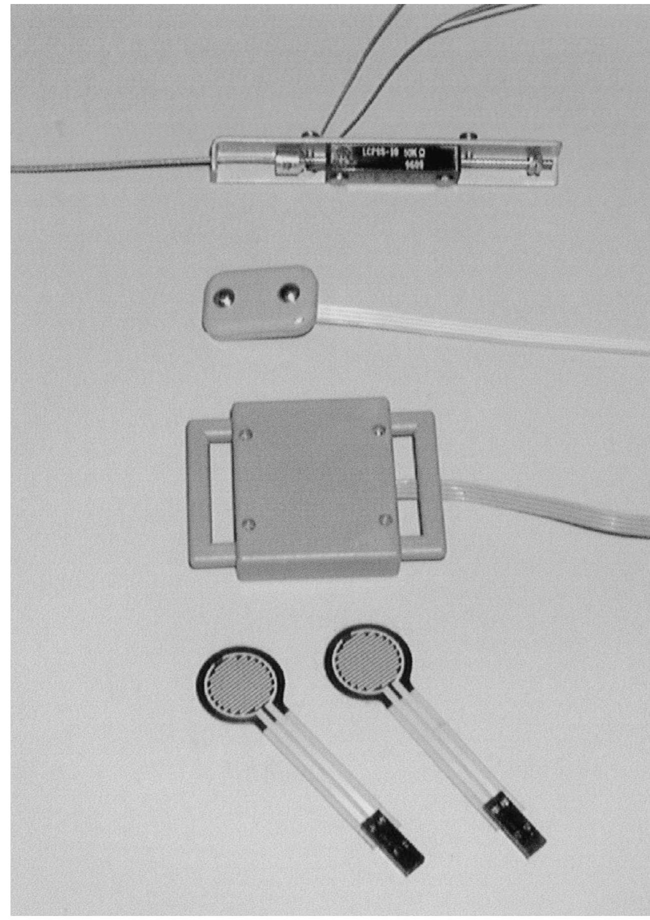

Figure 11. Input devices (from top): Linear transducer—Servo; myo-electrode; harness switch; force sensing reducer—touch pad.

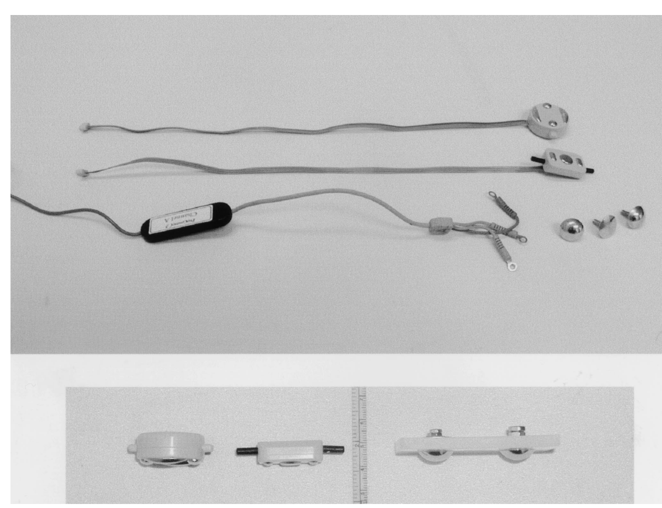

Figure 12. Comparison of Otto Bock (top figure–upper two electrodes; bottom figure–left) and Motion Control Style (top figure–lower electrodes; bottom figure–right) electrodes.

INPUT DEVICES

Input devices (Figure 11) for microprocessors include myo-electrodes, switches, servo type actuators, and FSRs. Myo-electric control involves the collecting and filtering of surface

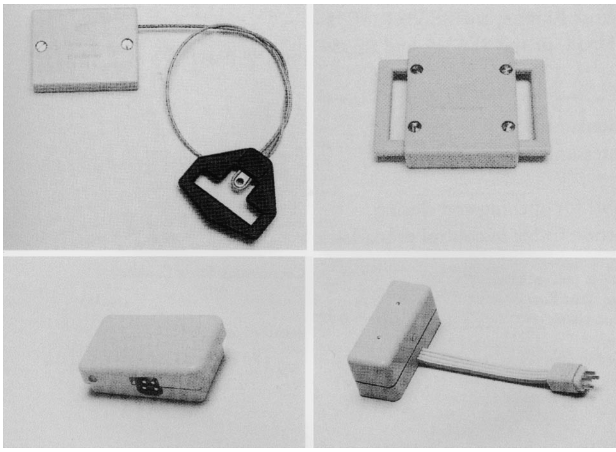

Figure 13. Switches. Clockwise from top left: cable pull switch, harness pull switch, rocker switch, and pressure or bump switch. Switches can be momentary (function or activation occurring only when the switch is actuated) or latching (function or activation occurring until switch is cycled again).

EMG signals generated through co-contraction of the muscle to actuate an electric motor. As electrode technology progresses, further analysis of electromagnetic disturbance (ESD) management as found in Otto Bock systems will warrant further investigation. This aspect of electrodes is beyond the scope of this article.

Myo-electrodes come in various sizes (Figure 12) with compatibility limits among different commercially available systems. Myo-electrodes are further differentiated by the designation of remote or non-remote. Remote and non-remote refers to the placement of the preamp electronics. Remote electrodes do not have the preamp electronics housed within the electrode assembly. Examples of remote electrodes are those used in the Motion Control type of electronics. Advantages of the remote electrodes include protection of electronics in the area of perspiration and environmental influences.

Non-remote electrodes, such as the Otto Bock type electrodes, house the preamplifier and electrode in the same casing. Although there is an increased risk of perspiration affecting the electrode and internal electronics, these types of electrodes reduce the amount of space needed to house electronics within the prosthesis or frame and reduce the size of the wire harness as well as the number of electrical connections. This can have an affect on reliability.

Each type of electrode has its specific patient application. In the clinical setting, electrodes should be chosen considering factors such as soft tissue to bone ratio, presence of scar tissue, and interface design. It is important to note that the Motion Control style remote electrodes do allow the maintenance of a suction type socket fit, as an airtight seal is created about the electrode. This type of negative pressure environment cannot be maintained with other types of electrodes and can be critical to prosthetic suspension, comfort, and moisture control, preventing perspiration from escaping into the area between the interface and frame.

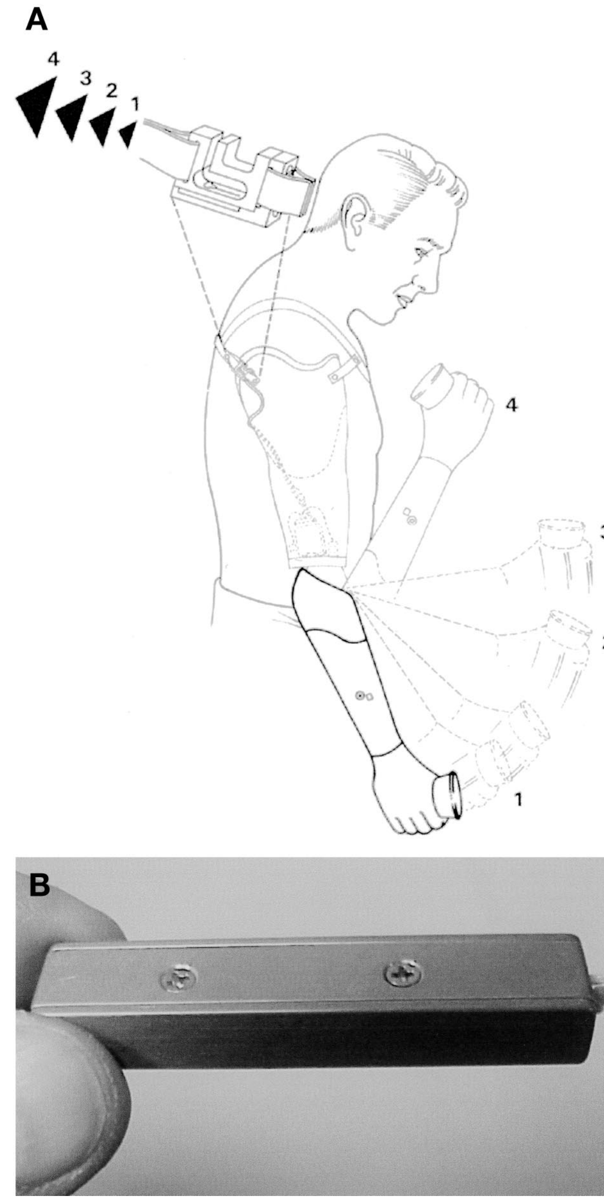

Figure 14. A: Linear Transducer from Liberating Technologies (courtesy of Liberating Technologies, Inc.). B: Direct relationship of force to elbow positioning can be found in the Motion Control ServoPro force sensor (Image courtesy of Motion Control, Inc.).

The use of microprocessors enables switches to be utilized in multiple applications although proportional control is absent. Switches come in a wide variety of presentations (Figure 13). Harness type switches rely on excursion or some type of pull to actuate the switch. Depressing the switch with a chin, phocomelic finger, residual limb, or contralateral hand actuates another type of switch, often referred to as a push or "nudge" switch. This switch may be placed distal to the axilla along the medial aspect of the transhumeral frame or on the medial aspect of the forearm on a transradial level amputee and pushed (through humeral abduction) when actuation is desired. More advanced switches are found in the multiple position type application. The typical application for a multiple position switch would be one in which three positions are utilized. The first position is a resting position in which no function occurs. The second position allows for functions such as wrist pronation. The third position allows for wrist supination. Furthermore, switches can be momentary (provides brief actuation while the switch is activated) or latching (provides function until switch is fully actuated again).

Servo type actuators come in two varieties (Figure 14). The linear type potentiometer is a servo input device that translates linear motion or excursion into proportional type function. Examples of this input device are Liberating Technologies' Linear Potentiometer (Figure 14A) or Otto Bock's Linear Transducer (in beta site testing at press time). The second variety is the force sensing type servo (Motion Control's ServoPro; Figure 14B). The force-sensing servo translates information gathered across a strain gauge and interprets this to proportionally actuate a device when programmed through a microprocessor or electronic system. Both types of servos provide increased proprioception through the association of force or linear pull (excursion) as it is related to proportional function. Although force-sensing servos require less excursion, the learning curve required to master finite control is greater than linear potentiometers that utilize excursion and gross body movement, which is easier for the patients to reproduce initially.

The FSR represents another type of input device applicable to the servo classification. These input devices consist of a force-sensing resistor matrix, which interprets pressure in a proportional manner. FSRs are actuated by movement of the shoulder complex in the shoulder level amputee as well as a residual humeral neck or the phocomelic finger. These types of input devices represent a low profile solution, providing an inexpensive proportional input device. Special care in FSR application into the prosthetic interface is critical to the success of the FSR input device. Improper installation will result in premature failure and greater expense secondary to perspiration, moisture, or uneven shear force.

PROGRAMMING METHOD

Programming the on-board microprocessor in a prosthesis to a specific user's requirements is currently accomplished using three different approaches. Adjustments to the electron-

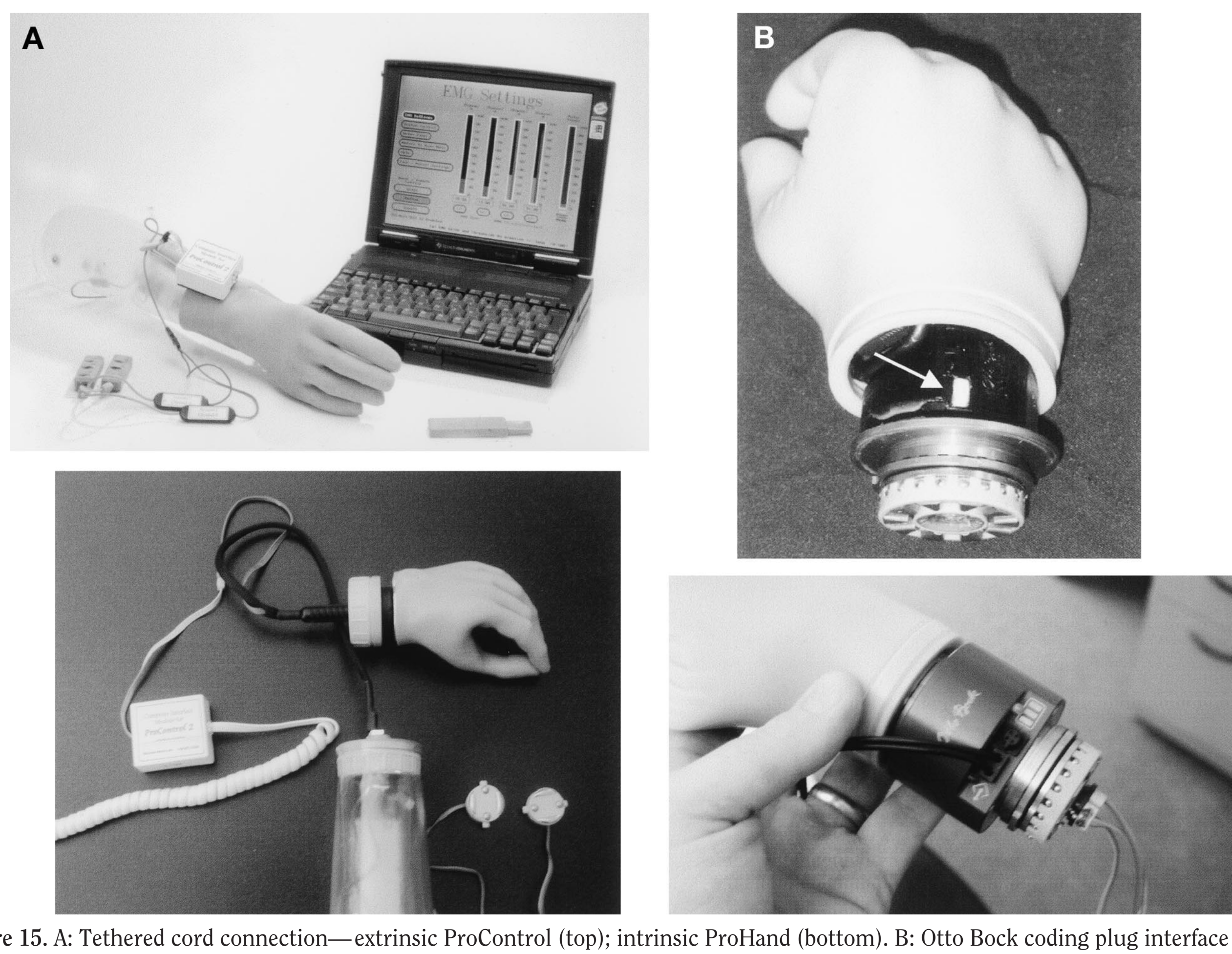

Figure 15. A: Tethered cord connection—extrinsic ProControl (top); intrinsic ProHand (bottom). B: Otto Bock coding plug interface method with white plug inserted (top); Otto Bock MyoCom connecting between the hand and wrist coupling (bottom).

ics are made through a tethered cord connection, radio wave type interface communication, or coding plug method (Figure 15).

OVERVIEW OF MICROPROCESSORS

Several benefits (as discussed previously) exist in the use of a microprocessor for the individual with upper limb deficiency. These benefits include: ease of modification of control parameters, reduction of expense and time during trial fitting period, increased user involvement and input during initial prosthetic management, control strategy versatility, and advanced myo-signal filtering algorithms. Many fundamental differences exist among microprocessors. Fundamental differences are investigated here, using objective and subjective comparisons to discern the characteristics that make each processor unique in clinical application.

Inclusion criteria for this evaluation were formulated with respect to the Ease of Use Guidelines set by the PC Quality Roundtable.[13] Selections were limited to commercially available microprocessors used in upper extremity adult fittings within the United States, provided that each microprocessor:

1. included written instructions for both the prosthetist and patient;
2. can (and has in the past) provide training in the use of the processor and associated manufacturer's components; and
3. demonstrated available, dedicated customer service.

A rating system approach, commonly utilized in the technology field, provides comparison parameters. A point system illustrates processor differences.

OBJECTIVE COMPARISONS AND RATING PARAMETERS

Weight of the microprocessor:

$\leq$15 g = 4 $<$ 20 g = 3 $<$ 25 g = 2 $>$ 25 g = 1

Power supply versatility

Internal or external only = 1 Both types = 2

Interface intrusiveness

Tethered cord = 2 Coding plug = 1

Control scheme versatility

1 point each for single site, dual site, servo, and switch

Warranty guideline of the particular microprocessor

1 point for each year

SUBJECTIVE COMPARISONS AND RATING PARAMETERS

Interface method/programming ease

Coding plugs = 2 Tethered cord = 1

Fabrication specifics

1 point each for provision of fabrication dummies and clearance tolerances

Hybridization or the ability to utilize other manufacturers' components

Yes = 1 No = 0

Currently, only three manufacturers of programmable microprocessors at the transradial and hybrid type levels met inclusion criteria for this study (duration February 2001 to August 2002): Otto Bock, manufacturer of SensorHand and DMC plus; Motion Control, manufacturer of ProControl II extrinsic and intrinsic ProHand; and Liberating Technologies Incorporated, manufacturer of Programmable Vari-Grip III. Each system possesses unique characteristics that make it attractive or advantageous in specific clinical situations. Comparisons are discussed here and summarized in Table 1.

OTTO BOCK

PHYSICAL EVALUATION

Otto Bock systems (Figure 16) are provided with written instructions. Weights of the intrinsic microprocessors are 9 grams for the DMC Transcarpal, 12.5 grams for the Standard DMC, and 15 grams for the SensorHand. The processors are primarily housed in terminal devices and a separate four-channel controller is needed for addressing electric wrist rotation control. Otto Bock systems are compatible only with Otto Bock power supplies because these processors communicate with the battery to regulate voltage as well as temperature parameters. Warranty guidelines are explicit and are 1 year in length.

INTERFACE METHOD AND PROGRAMMING

At this time, the commercially available Otto Bock systems utilize coding plugs in conjunction with their Myoboy or Myosoft software. The download method requires the removal and installation of coding plugs.

Beta site testing is currently underway using MyoCom software and a tethered interface to allow for more comprehensive adjustment of the microprocessor function. The customizing of gains and thresholds will be facilitated through a tethered cord connection at the battery box for terminal devices without a quick disconnect wrist and at the coaxial plug for terminal devices with a quick disconnect wrist. Processor data and patient information can be accessed with a laptop.

CONTROL SCHEME VERSATILITY

Otto Bock systems utilize a single site or dual site control. Input devices that are supported include myo-electrodes and switches (later with use of a linear transducer upon conclusion of beta-site testing). Fine-tuning of EMG con-

Table 1. Objective and subjective comparisons of three programmable microprocessors

	Otto Bock	ProControl	VariGrip
Objective Comparisons			
Weight Parameters	4	3	4
Power Supply Versatility	1	2	2
Interface Method	1	2	2
Control Scheme Versatility	3	3	4
Warranty	1	2	1
Totals	10	12	13
Subjective Comparisons			
Interface Programming Ease	3	2	2
Fabrication Parameters	2	1	1
Hybridization	0	1	1
Totals	5	4	4
Total Score for Each Processor	15	16	16

trol parameters and control schemes utilize a variety of external approaches including coding plugs, Myoboy feedback, and four channel controllers with associated adjustment cap.

INTERFACE AND PROGRAMMING EASE

Written instructions and ease of coding plug use facilitate programming. The primary disadvantage of the coding plug approach is that prosthetic adjustment or coding plug installation requires disruption of function because the hand shell must be partially removed to access the coding plug port. Removal of the hand shell can require strength and dexterity by the prosthetist.

FABRICATION CHALLENGES

The Otto Bock systems provide the best clearances with little or no additional internal considerations, besides length, that dictate the use of a wrist rotator. With the vast availability of component dummies, fabrication challenges are reduced. Currently, the Otto Bock system utilizes only an external removable battery supply, which will exhibit a circumference increase in the area in which this battery is placed. Lithium ion batteries are available in two sizes, in contrast to the one standard sized Otto Bock NiCad battery. Unlike the NiCad battery, the lithium ion battery box and battery casing are flush with the outside of the prosthetic frame improving cosmesis while protecting the battery from external edge pressure.

UNIQUE CHARACTERISTICS OF THE OTTO BOCK MICROPROCESSORS

Engineering and design of the Otto Bock systems are the result of more than 30 years of progressive electric upper

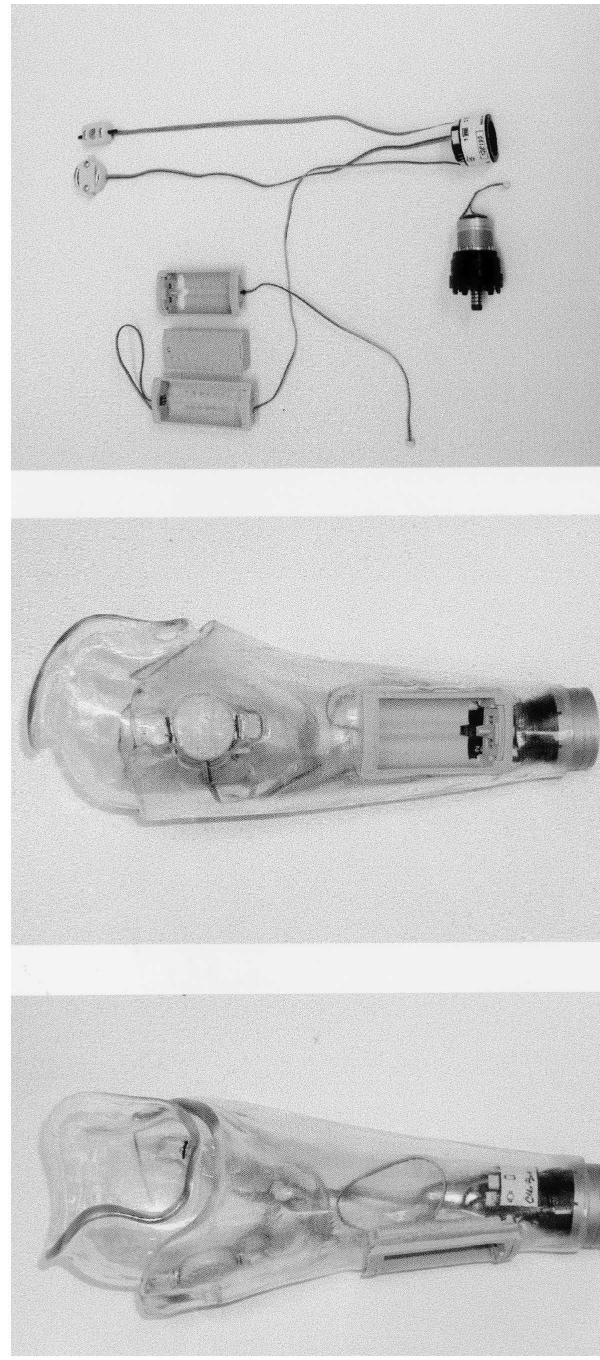

Figure 16. Otto Bock microprocessor; component size and clearance.

extremity products. The SensorHand provides the prosthetist with interface methods that do not require the use of a laptop. This adds to Otto Bock's "out of the box reliability" reputation that has come to be the gold standard of the field. In addition, the predefined algorithms governing the closed loop functions discussed earlier provide the patient with functional benefits that allow the microprocessor to adjust in different functional activities. These algorithms support Otto Bock's electric prosthesis objective of "taking the mental effort away from the patient and placing it in

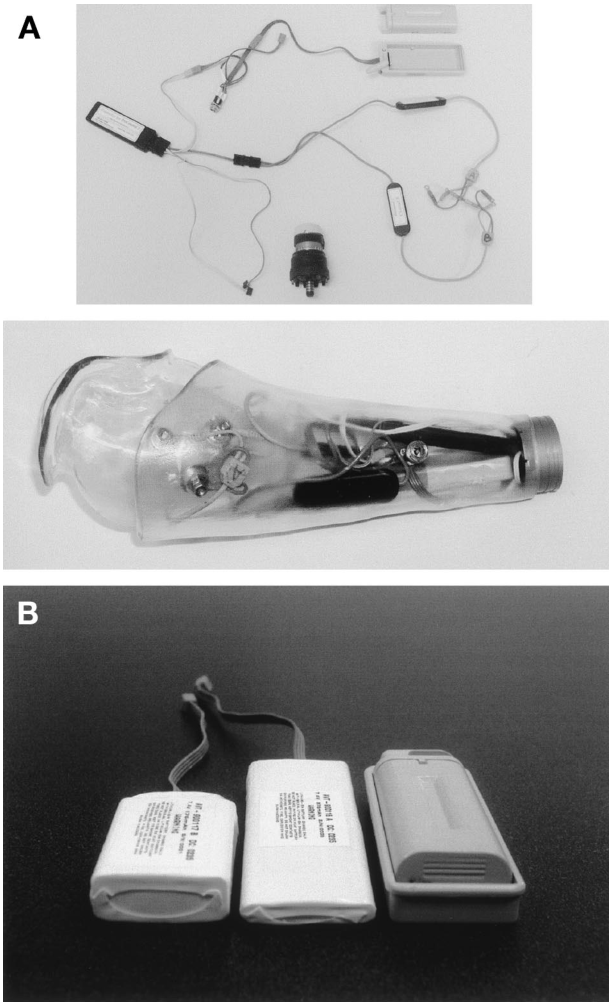

Figure 17. A: ProControl II microprocessor. Note the size of the processor does not allow for wrist use secondary to tight clearances. B: The new internal battery option for the ProControl II Microprocessor, introduced in 2002, allows for tighter clearances.

the prosthesis” (Hans Dietal, PhD, Otto Bock, personal communication).

PROCONTROL II

PHYSICAL EVALUATION

Clear and thorough written instructions are provided with the ProControl II (Figure 17A). The weight of the extrinsic microprocessor is approximately 19 grams. The ProControl II can be powered by either an internal (Figure 17B) or external lithium ion supply at a common application of 7.2 volts. This type of microprocessor is compatible with other commercially available power supplies and can be wired in series to provide 14+ volts. A 2-year warranty is included with this microprocessor. The ProControl II uses a tethered cord connection through a battery box port. Separate ports are included for socket mounting when utilizing the internal batteries. Processor data is available for upload and download, and patient data can be stored and recalled within a laptop PC.

CONTROL SCHEME VERSATILITY

At this time, the ProControl II offers dual site and single site myoelectric controls. Input devices include remote and nonremote myoelectrodes and a force-sensing servo. The ProControl II offers virtually infinite fine-tuning of the EMG signal and multiple adjustment windows to calibrate cocontraction switching.

INTERFACE AND PROGRAMMING EASE

Ample written instructions and help screens to ease programming accompany the ProControl II. Care and practice are needed when learning to upload or download patient files because inappropriate technique and a cumbersome software interface can cause loss of information.

FABRICATION CHALLENGES

Additional space between the inner socket and frame to accommodate the preamps and electrode wire harness can be a fabrication and cosmetic challenge. Furthermore, the ProControl II system may not be acceptable cosmetically for female patients or individuals with long transradial residual limbs because of the size of the microprocessor (when intrinsic ProHand is not used), remote preamps, and wire harness.

UNIQUE CHARACTERISTICS OF THE PROCONTROL II MICROPROCESSORS

The Motion Control family of processors and components was the first to provide proportional control in a reliable electronics package. The manufacturer was instrumental in many of the early studies indicating proportional control benefits that now are clinical standards. The ProControl II exhibits a processor package that is both easy to use and is intuitive to both patient and practitioner. The detailed instructions, quick set up, and directions affixed to the battery charger provide exceptional ease of use and are complemented by the lengthy warranty and durability of the components.

PROGRAMMABLE VARIGRIP III

PHYSICAL EVALUATION

Written instructions are provided with the programmable VariGrip III controllers (Figure 18). The weight of the extrinsic microprocessor is approximately 14.6 grams. The microprocessor utilizes multiple internal and external power supplies available from Liberating Technologies, Inc. or other manufacturers. The VariGrip III microprocessors have a 1-year warranty.

INTERFACE METHOD AND PROGRAMMING

The Programmable VariGrip III utilizes a tethered cord connection and a separate port. Processor data are available for upload and download, and patient data can be stored and

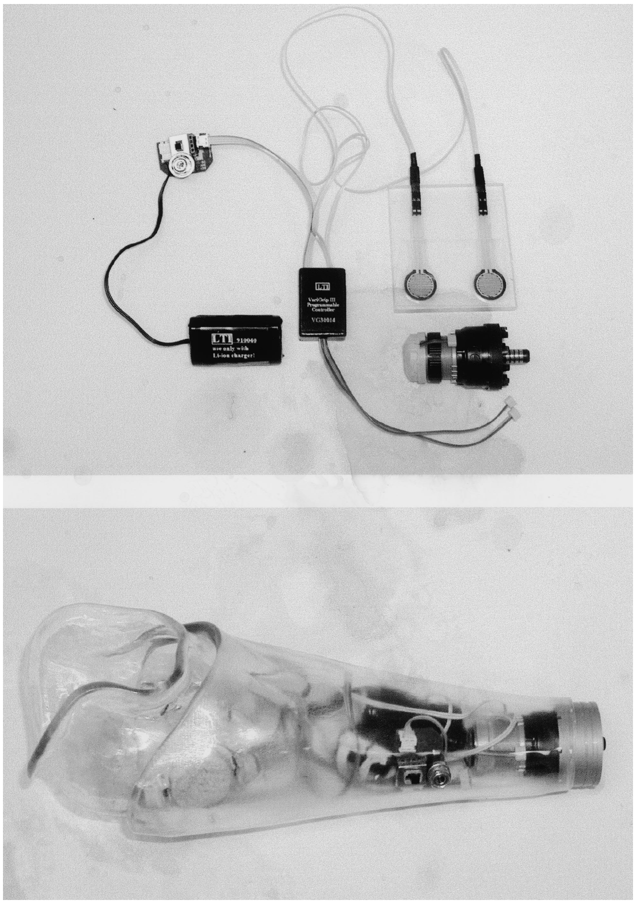

Figure 18. Programmable VariGrip microprocessor, shown with FSRs because it is the only microprocessor in our investigation that can utilize this input device. Appropriate clearances illustrated.

recalled. Unique to this type of processor is the collection of usage data regarding the use patterns of the prosthesis.

CONTROL SCHEME VERSATILITY

The Programmable VariGrip III represents the most versatile prosthetic controller. It has dual site and single site control capabilities, utilizes all input devices and has infinite fine-tuning of the EMG signal. Patient evaluation modes streamline and aid in the initial fitting. Myoelectric signal interpretation is not as refined, with reduced speed control of the terminal device.

INTERFACE AND PROGRAMMING EASE

The VariGrip III controller has undergone modification in programming and adjustment screens (Figure 19). The initial screens reviewed were not intuitive and difficult to manipulate, requiring initial programming to be performed by the manufacturer. When utilizing special input device and wiring applications, the manufacturer is skilled at customizing control scheme creation to meet specific patient requirements.

FABRICATION CHALLENGES

The Programmable VariGrip III processors incorporate many innovated designs allowing the controller or batteries to wrap around the rotator or distal aspect of the socket. These types of applications require preplanning regarding component selection and placement.

UNIQUE CHARACTERISTICS OF THE VARIGRIP III MICROPROCESSOR

Liberating Technologies, manufacturer of the VariGrip III microprocessor, are skilled at modification and adaptation of components, providing compatibility with many other manufacturers' components. To date, the VariGrip III represents the most versatile controller, accepting up to five inputs controlling up to four motors. Progressive thinking by the manufacturer has provided such product adaptations as the wrap-around VariGrip II (Figure 20) that can be used in conjunction with a wrist rotator requiring minimal additional clearance.

DISCUSSION

Beyond the scope of the initial investigation is the discussion of automatic or predefined microprocessor functions versus adjustable microprocessor functions. Examples of predefined functions that are not adjustable are the DMC (Dynamic Mode Control) schemes and closed-loop controller functions found in the Otto Bock Systems, power supply monitoring, and auto-calibration of terminal device function. Additional variables for further study include rate-sensitive versus threshold-sensitive inputs, EMG sensitivity and filtering capabilities, as well as myo-signal strategies such as first-come, first-serve and differential schemes. Objective investigation of these characteristics will require the control of several variables. Methods to accurately review these characteristics are currently under investigation by the authors.

Microprocessors have many objectives, one of which is the enhancement of patient function. Patient function is realized when the myo-signal exceeds the threshold. For individuals who present with co-contraction tendencies either caused by surgical procedure, deconditioning, or other variables, muscle site differentiation in the past was very difficult if not impossible. Patients either utilized a less functional electric option (such as single site or switch control) or were deemed not candidates for electric upper extremity prosthetic management. An example of this is a patient who is able to contract his A muscle group with little or no antagonist activity but exhibits antagonist muscle activity (~35 mV) when contracting his B muscle group. This presentation can cause inadvertent opening/closing of the prosthetic terminal device. By raising the A threshold up to just above the antagonist muscle contraction level (~40 mV), the co-contraction is addressed and patient terminal device control is obtained.

During the evolution of third-generation upper extremity electronics, functional challenges following commercial re-

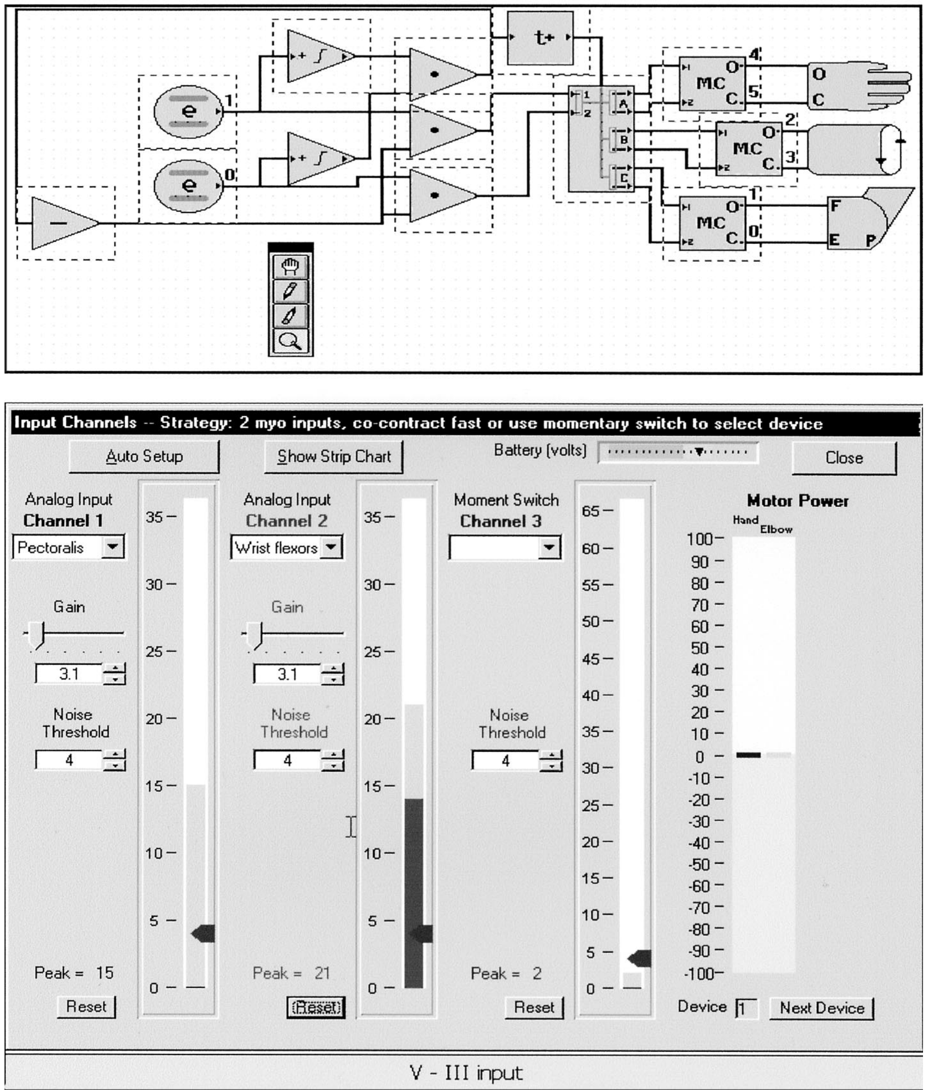

Figure 19. Initial VariGrip III window (top) and revised VariGrip III window (bottom).

lease of microprocessors have necessitated revamping of original concepts or indication for increased care in handling electronics during fitting. One such challenge was represented in the auto-calibration feature of the ProControl II. Auto-calibration is a feature that allows the individual's prosthesis to self adjust as muscle strength (EMG signal) and endurance change throughout the day. In its purest form, the patient merely turns the processor off and on again. When powering up the prosthesis, the patient contracts each muscle group individually for a preset period of time, the microprocessor records the muscle contraction levels and adjusts the prosthetic gains and thresholds for optimal control. This type of auto-calibration mechanism currently does not allow for further adjustments of muscle contraction rates for co-contraction switching. This additional feature would complete the auto-calibration features and provide a powerful tool for the patient and prosthetist.

Specifically, the challenges of first iteration third-generation electronics are represented in the physical size of the controller (Figure 21). Much of the field of upper extremity prosthetics could be far more advanced if there were no limitations in clearances or weight tolerances. The goals of reduced microprocessor size, electronic connections, and components are on the forefront of every manufacturer's research and development protocol. Tethered cord connections represent a reliable yet limiting interface method. Depending on the length of the wire tether, unrestricted functioning with the prosthesis is compromised and accurate analysis of patient use and function varies.

Specific first iteration challenges exist for each manufacturer. Currently, the Otto Bock system utilizes external Caucasian colored power supplies only. External power supplies are not always consistent with the cosmetic demands of the wearer. While programming is easy, the mainstream commercially available Otto Bock systems require disrupting prosthetic function to manually replace coding plugs. Otto Bock systems are not compatible with other microprocessors and, therefore, may be viewed as limiting patients' functional options. The Otto Bock system requires more physical or

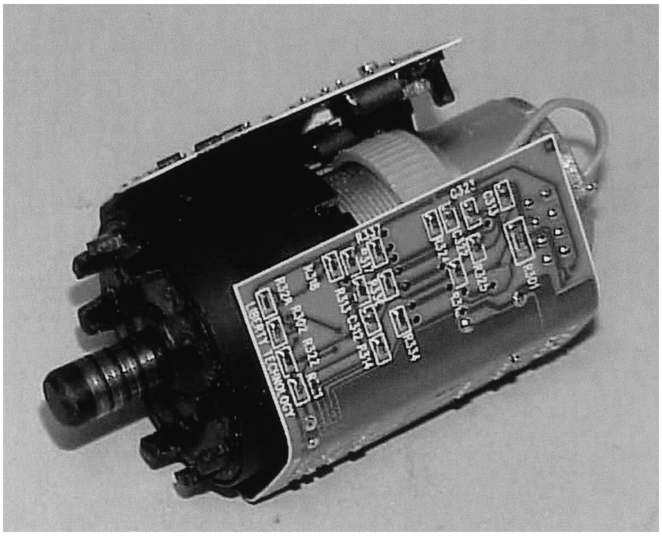

Figure 20. The wrap-around VariGrip II processor illustrates progressive thinking and respect of clearance tolerances.

Figure 21. Size comparison between the VariGrip III and ProControl II extrinsic processors. Note the ProControl II is available as an intrinsic processor within the Motion Control Hand.

microvolt effort to operate the system compared with other manufacturers. This is partly due to the limited EMG and threshold manipulation in the current coding plug library. In the authors' experience as a testing location for the beta MyoCom and customizing software, sufficient EMG gain and threshold manipulation will be obtainable in the future for even the most complex of patient fittings. At this point the widespread allowance of customizing will be on a case-by-case basis based on prosthetist experience, training, and certification. This is partly due to the complex reactions of the predefined algorithms affecting the output as the input characteristics are manipulated.

The ProControl II has exhibited compatibility challenges with the different types of Microsoft Windows applications among different manufacturers' laptops, specifically, issues with IBM notebook computers requiring a patch program. This is partly due to the current DOS interface that runs simultaneously with windows applications. Currently, the authors are testing the Windows version of the interface software and find enhanced compatibility. Early on in the development of the ProControl II, the beta site testing revealed interface failures, especially when wiring batteries in series for increased voltage and subsequent increase in terminal device speed, although most of these issues have been resolved.

The Programmable VariGrip was challenged by the difficult programming modes it initially provided. These programming screens were difficult to read and have been redesigned recently. The Programmable VariGrip III's greatest advantage can be a disadvantage as well. Across-the-board compatibility can be difficult to maintain with the rapid introduction of new electric components. Nonetheless, Liberating Technologies represents the most progressive of the manufacturers in their component compatibility and technical support facilitating such compatibility.

FUTURE STUDY

This article represents both a snapshot of existing microprocessor technology and a starting point for its evaluation. Future testing will follow guidelines commonly used in the technology field such as the Ease of Use/PC Roundtable.[13] These guidelines are adhered to by computer manufacturers and provide the baseline for comparison. The rating system found in the "Initial Experience Prediction Checklist"[14] is currently under revision for use in future prosthetic microprocessor study. Future study will include prosthetist/patient ease of use. Past technology studies have shown that poor ease of use is one of the primary reasons consumers do not commit to such technology. Study of these parameters will require the use of a range of prosthetists of differing skill levels. These practitioners would then complete an interactive "Initial Experience Prediction Checklist" providing results that are indicative of the specific microprocessors' ease of use at both the prosthetist and patient levels. Concurrent with the ease of use study, the authors will analyze microprocessor functionality through the investigation of adjustable parameters with respect to constant, repeatable myosignals. This type of evaluation will allow objective comparisons of microprocessor adjustability and effectiveness.

CONCLUSION

The recent emergence of microprocessor-based prosthetic control for the individual with upper limb deficiency has greatly expanded the spectrum of treatment options and inclusion criteria for this patient population, requiring further study of its effect on upper limb prosthetic function. Control options are now available for individuals who were at one time not candidates for such prosthetic management.

Although one of the most important advantages of the use of microprocessors in upper limb prosthetics is the enhanced EMG filtering algorithms, for many it is also the most subtle. The use of microprocessors will require special care by all members of the upper limb rehabilitation team. Enhanced function, not necessarily "easier" function, should be one of the goals of microprocessor use.

In 2002 the Centers for Medicare and Medicaid Services (CMS) introduced a reimbursement code for microprocessors (L-code L6882, Microprocessor control feature). As reported by manufacturers, this recognition has increased interest in and use of microprocessors in upper limb prosthetics. Like the graphic equalizer in line with a sound system, the microprocessor delineates, filters, and enhances input characteristics to produce the desired output: optimal prosthetic function.

Microprocessor benefits include:

1. Provides the ability to modify control options and adjust input characteristics quickly throughout all stages of prosthetic management without purchasing or exchanging components.
2. Allows for expeditious provision of prosthetic management, facilitating return to function in agreement with the Malone's guidelines for optimal return to function.
3. Allows more complex filtering of the EMG signal and ease in changing control thresholds and sensitivity of the prosthesis as the users' strength and ability evolve.
4. Real-time input signal analysis providing the early detection of residual limb changes.
5. Ability to document and store patient information, allowing for long-term treatment goals to be monitored.
6. Utilization of complex algorithms to inherently adjust to various situations unknown to the patient, "reducing the mental effort" necessary to function with an electric prosthesis.
7. Incorporation of predefined "behind the scenes" programs that monitor and respond to prosthetic functioning.
8. Improved patient functionality and maximization of a patient's rehabilitation potential.

Specific indications for microprocessor augmentation can be derived from our initial 18-month investigation. These indications include patient presentations of reduced muscle EMG potential, frequent EMG muscle site fatigue, general deconditioning of musculature secondary to the natural progression of residual limb atrophy and/or the absence of prosthesis use, and the further incorporation of prosthetic functions to more closely address the functional loss of the upper extremity amputee. The use of a microprocessor allows for ease and longevity of prosthetic control. This in turn can increase bimanual functioning, which will further reduce adverse stresses associated with overuse of the sound limb. While adjustable microprocessors will certainly allow for expeditious return to function, it should not take the place of a well-structured rehabilitation plan that focuses on all aspects of upper extremity care, from pre-prosthetic residual limb conditioning to long-term post-prosthetic functional goals.

ACKNOWLEDGMENTS

The authors thank Hans Dietl, Otto Bock; William Hansen, MS, Liberating Technologies; Pat Prigge, CP, Otto Bock; Harold Sears, PhD, Motion Control; and T. Wally Williams, MS, Liberating Technologies for providing the microprocessors studied here and for valuable discussions.

REFERENCES

1. Malone JM, Fleming LL, Roberson J, Whitesides TE, Leal JM, Poole JU, Sternstein-Grodin R. Immediate, early, and late postsurgical management of upper-limb amputation. *J Rehab Res Dev* 1984;21:33–41.
2. Heckathorne CW. Components for adult externally powered systems. In: Bowker JH, Michael JW, eds. *Atlas of Limb Prosthetics, 2nd ed.* Chicago: Mosby, 1992:151–74.
3. Childress DS. Control of limb prostheses. In: Bowker JH, Michael JW, eds. *Atlas of Limb Prosthetics, 2nd ed.* Chicago: Mosby, 1992:175–198.
4. Lamb DW. State of the art in upper-limb prosthetics. *J Hand Ther* 1993;6:1-8.
5. Prosthetic technology: Neural interface advances could increase limb prosthetics utility. *Prosthet Orthot Eng* 1997;2:54.
6. Kyberd PJ, Chappell PH. Object-slip detection during manipulation using a derived force vector. *Mechatronics* 1991;2:1–14.
7. Nightingale JM. Microprocessor control of an artificial arm. *J Microcomput App* 1985;8:167–173.
8. Kyberd PJ, Holland OE, Chappell PH, Smith S, Tregidgo R, Bagwell PJ, Snaith MM. A two degree of freedom hand prosthesis with hierarchical grip control. *IEEE Trans Rehab Eng* 1995; 3:70–76.
9. Datta D, Brain ND. Clinical applications of myoelectrically controlled prostheses. *Crit Rev Phys Rehab Med* 1992;4:215-239.
10. Hortensius P, Onyshko SA. Microcomputer-based prosthetic limb controller: design and implementation. *Ann Biomed Eng* 1987;15:51–65.
11. Research and related work in conjunction with fellowship lecture. "Microprocessors in Upper Limb Prosthetics," Chris Lake, CPO, FAAOP, for the American Academy of Orthotists and Prosthetics Certificate Course in Upper Limb Prosthetics.
12. Lake C, Miguelez JM. Overview of microprocessors in upper limb prosthetics. Presented at the ISPO 2001 World Congress, Glasgow, Scotland, July 1-6, 2001.
13. Ease of Use Roundtable Publications. Roundtable update October 26, 2000. Improving PC Ease of Use, February 2000.
14. Initial Experience Prediction Checklist versions 1.0 and 1.1 White papers and publications @ eouroundtable.com.