Digital Approaches to Myoelectric State Control of Prostheses

ABSTRACT

The design of a new three-state myoelectric control system is presented. This controller determines its operating state from the initial rate of increase of the myoelectric signal, and the concept is realized in great measure through digital logic techniques. Proportional control of both active states (same dynamic range) is a unique feature of the controller.

A microcomputer was interfaced in a simple way with myoelectric potentials to simulate the three-state controller described and to simulate various other state-determined control methods (some multifunctional). This was found to be a valuable method of evaluating control schemes without building the actual devices.

INTRODUCTION

Since the introduction of myoelectric or electromyographic (EMG) control to limb prosthetics, there have been many attempts to use myoelectric signals for the control of prostheses with multiple degrees of freedom, and to do this with a limited number of muscle sites. These attempts have been prompted because arm amputees with high-level amputation locations frequently need multifunctional artificial arms but have limited muscle sites that are practical as myoelectric signal sources.

The most successful myoelectric artificial limbs, below-elbow myoelectrically controlled hands, may be considered to be wasteful of muscle sites because two sites (finger extensors and flexors) are usually used to control one degree of freedom (hand opening-closing). Dorcas and Scott (1) introduced the three-state single-site control concept in 1966; the method is more conserving of muscle sites because one muscle site controls one degree of freedom. Five-state single-site control (2) has also been used. These, and other state-determinant methods, often lack strong physiological underpinnings. Nevertheless, state approaches have been successful from a clinical viewpoint (e.g., Scott (3), Schmidl (4)) and probably will be used for some time to come.

Graupe (5,6) has introduced the idea of multifunctional control from one muscle site using computer-based signal analysis techniques. However, this concept awaits further development before it can be determined how it will impact the clinical problem.

This paper first presents a digitally-based circuit design for a three-state, rate-sensitive single-site controller, and then presents ideas on how various multifunctional, multistate concepts may be investigated and evaluated through microcomputer approaches. A simple method of interfacing myoelectric inputs with microcomputers is presented. This interface concept may have future applications in microcomputer-based myoelectric limbs.
THREE-STATE MYOELECTRIC CONTROL

In a three-state controller the myoelectric or electro-myographic (EMG) signal from the control muscle is classified as belonging to one of three groups. The classifying parameter can, for example, be the root-mean-square (RMS) amplitude of the EMG, or it can be the rate at which the RMS amplitude is changing (7). By detecting three different states of the EMG signal from one muscle site it is possible to control one degree of freedom (off, forward, reverse) in a prosthesis.

A three-state controller that is amplitude sensitive may have the characteristics shown in Figure 1. When the EMG level is below level T1 there is no output from the controller. For an EMG level that stays between levels T1 and T2 longer than time \( t_d \), output A is activated. Output A will stay on until the EMG level is no longer in the region between T1 and T2. When the EMG level goes above level T2, output B is turned on. Output B will continue until the EMG level drops to a value less than T2. A time delay, \( t_d \), makes it possible to directly activate or deactivate output B without activating output A.

The amplitude-sensitive three-state controller seems to work best with an on-off output characteristic. It is possible to let the amplitude of the EMG level above T2 proportionally control output B, but because the zone T1-T2 may occupy a large part of the dynamic range of the EMG signal, this may not be an effective approach. High levels of EMG may be required for full output from B in this semi-proportional arrangement, and this may result in muscle fatigue.

The rate-sensitive three-state controller is an alternate approach that some users find more desirable than the amplitude approach. A three-state controller that is rate-sensitive can have the characteristics shown in Figure 2. Childress (8) designed an early rate-sensitive three-state controller based on an idea of Colin Ruch. (The idea was conveyed in conversation by the late Colin Ruch, a biomedical engineer from South Africa, during the ACEMB Conference in Houston in 1968.) That controller used the natural rate-sensitive characteristics of a silicon-controlled rectifier (SCR) as the rate-detection circuit. Dillner & Hagg (7) first suggested the approach described here; their approach is easily realized with digital circuitry, and offers the added advantage of permitting proportional control, although they did not implement a proportional feature.

The general principle of the approach is illustrated in Figure 2. The block diagram of Figure 3 shows how we implemented this approach with a digital-type processing scheme.

![Figure 1](image-url)  
Diagram showing three-state characteristics of an amplitude-sensitive controller. A rectified and integrated EMG signal (EMG-level) in the interval T1 to T2 will activate output A and an EMG level in the interval above T2 will activate output B. Time-delay \( t_d \) makes it possible to activate output B without activating output A.

![Figure 2](image-url)  
![Figure 3](image-url)
The principle of operation is based on the average rate of change of the processed EMG signal over a specified time period, \( t_d \). If at \( t_d \) seconds after the signal crosses threshold \( T_1 \) the signal is greater than threshold \( T_2 \) \((T_2>T_1)\), then the average rate of change over \( t_d \) is greater than \((T_2-T_1)/t_d\). Otherwise it is less than this value. The state decision is based on this averaged rate of change of the signal, not on an instantaneous value of the somewhat noisy signal. It is possible to control the output in a quasi-proportional way by letting the EMG control the output (myo-pulse) drive, after the rate-based decision has been made.

**Description of Operation of Three-State Proportional Myoelectric Control Circuit**

The new three-state proportional myoelectric controller that we have developed is shown in block-diagram form in Figure 3 and diagrammed in detail in Appendix A. The amplified EMG signal is converted to a pulse-type signal in the myo-pulse processor. Figure 4.
FIGURE 3.
Block diagram of a three-state myoelectric control circuit. The function is described in the text.

FIGURE 4.
Illustration of the myo-pulse processing technique. The upper record represents a typical band-pass filtered electromyographic signal (EMG). When the absolute value of the EMG exceeds a threshold $V_t$, the output (lower record) saturates. The output will have a duty cycle related to the EMG amplitude.
illustrates this conversion. This so-called “myo-pulse” processing technique has been described elsewhere (9) and has proved to be a practical processing technique in myoelectric control. The power output to a drive motor may be driven directly with this signal, without electrical filtering. The digital-like myo-pulse signal is “gated” to the driver according to the decision made about initial rate of EMG increase.

The rectifier and integrator supplies the two comparators with a DC level that is proportional to the EMG level. When the EMG level reaches level T1 the output from comparator 1 goes on, this transition starts the timer. When the timer times out, after the td, the bistable latch is clocked. If, when the bistable latch is clocked, the output from comparator 2 is off, the latch will be set with output A on and output B off.

If, when the bistable latch is clocked, the output from comparator 2 is on (the output of comparator 2 will go on when the EMG-level exceeds level T2), the latch will be set with output A off and B on.

In other words, a low-rate contraction will open AND-gate A at the end of the time-interval td and a high-rate contraction will open AND-gate B at the end of the time interval td (~80 msec).

When either gate is open, pulses from the myo-pulse processor can pass through the gate to the actuator, providing proportional-like control of the prosthetic device.

AND-gate A or AND-gate B will remain open until the EMG-level drops to a value lower than T1. The driver circuit, when activated, provides power to the motor in the prosthetic device and provides damping to the motor.

The circuit as physically realized is shown in Figure 5. This circuit is identical in size to the two-site circuit used in the VANU myoelectric hand system. Therefore, it can be substituted for the two-site circuit when single-site control is required.

We have successfully used the system with three below-elbow amputees. Each was originally fitted with the SCR rate-sensitive circuit and subsequently changed to

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4This time out signal also enables the two AND-gates. In this way unwanted outputs are avoided while the timer is running.

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FIGURE 5.
Photograph of a three-state rate-sensitive myoelectric control circuit. The printed circuit board measures 3.5 x 4.4 cm.
the circuit described here because this circuit was simpler (less expensive, more reliable, and easier to adjust) and had proportional control of both hand opening and hand closing.

Clinical Experience

R.S. is a 34-year-old bank executive (Right B/E, electrical burns) first fitted with rate-sensitive myoelectric control of a hand prosthesis in 1968, when he was a college student. He could use only single-site control from wrist extensor muscles because the remaining flexor muscles cramped when contracted. He was converted to the single-site system described here in 1977 and used it daily until 1979 when he was converted to a two-site system, as the muscle cramping problem had gone away. R.S. operated the system easily, and rarely activated the wrong mode, although he found the single-site system required more attention to operate than the two-site system. It also could not be cycled between output states as quickly.

D.M. is a 31-year-old businessman who first received a single-site myoelectric hand system as an immediate postsurgical fitting in 1970. A punch press injury during summer work from college had resulted in a B/E amputation of his right arm. All flexor muscles of the forearm were lost in the injury and subsequent surgery. D.M. was converted to the system described in this paper in 1977 and continues to use the system daily.

W.V., a 47-year-old securities broker (Left B/E, Trauma), was referred to our laboratory in 1971 because he had only one below-elbow myoelectric site. Fitted that year, his system was upgraded in 1978 to contain the three-state system described. He continues to use this system.

All the amputees described operated the three-state system without difficulty on their first trial. Training sessions were not necessary. Quick muscle contractions are easily separated from slow ones. Because the users rarely made incorrect control commands it was not thought necessary to make laboratory measurements of accuracy. The systems clearly gave good control of a prehension prosthesis, although the control was not as automatic or quick as with two-site control of the same kind of prostheses. Experience indicates there is a small percentage of below-elbow amputees who cannot use two-site control for whom the circuit described is beneficial. The system can be used for higher-level amputations, but our experience has been limited to below-elbow amputees.

**FIGURE 6.**

Block diagram of a microcomputer-based myoelectric control system that can utilize one or two electrode inputs and produce up to seven output modes in ways determined by the control program. RAM (Random Access Memory), MPU (Microprocessing Unit), PIA (Peripheral Interface Adaptor), D,E,F,G,H,I, (AND-gates).
Multi-State Proportional Myoelectric Control Using Microcomputer Techniques

One of the problems associated with “state” approaches to prosthesis control, particularly multifunctional control, is that, frequently, various concepts need to be experimentally evaluated. Evaluation may be expensive and arduous if new circuitry must be designed for each new concept. Our goal has been to develop a microcomputer-based device which would allow different control algorithms to be examined by changes in computer program rather than by hardware changes.

The system was developed to handle up to two myoelectric signal inputs, although this could be expanded to any desired number. Proportional or on-off output drives have been provided.

Figure 6 shows the control system in diagrammatic form. Although the system was developed for rapid laboratory evaluation of control concepts, it has potential for future use in actual prostheses. The use of a microcomputer-based controller in a self-contained battery-powered prosthesis should become common in the near future. In fact, a generalized hardware system compatible with a wide variety of control schemes and prosthetic designs seems possible. In that way one hardware system could easily be used for many control techniques commonly used today. Standardized hardware could reduce cost of electronic controllers for artificial limbs.

Description of Operation

The EMGs from two muscle sites are processed as described in Figure 4. The outputs from the processors are logically AND-ed with a high-frequency clock in gates A and B. By letting the microprocessor count the number of pulses coming from gates A and B during a fixed time interval, a measurement of the EMG level in the muscles is obtained. The technique of letting the output from the EMG processor gate pulses from a high-frequency clock has been described previously in a paper by Ichikawa et al. (10).

With information concerning the EMG level in the two control muscles, the microprocessor can make a decision on what motion the user wants the prosthesis to perform. This decision can be made according to a resident control algorithm. When the decision is made, the appropriate gate in the gate-array (D through J) will be opened by the peripheral interface adaptor (PIA). The outputs of the gates may be operated in either an on/off mode or in a proportional, pulse-width-modulated, mode, depending on the setting of switches in front of gates D through I. The outputs from the two myo-pulse processors are logical OR-ed by gate C, producing a signal that is proportional to the boolean sum of the outputs from the myo-pulse processors. This signal can be gated to drive the actuators in a proportional way if the switches are set in the proportional mode.

Several control algorithms have been laboratory-tested. One successful algorithm tested (based upon subjective laboratory experiments with amputee and non-amputee subjects) was a seven-state controller that employed two muscle sites. The state relationships are shown in Figure 7. Table I summarizes that approach.

The muscle space may be partitioned in many other ways (e.g. see Childress (11) et al.). The computer permits rapid experimental examination of various parti-
tioning schemes and allows rapid adjustment of parameters within a particular scheme. Software changes, as opposed to hardware changes, make this possible.

<table>
<thead>
<tr>
<th>rate of contraction</th>
<th>principal muscles</th>
<th>output function</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>triceps</td>
<td>hand opening</td>
</tr>
<tr>
<td>low</td>
<td>biceps</td>
<td>hand closing</td>
</tr>
<tr>
<td>low</td>
<td>triceps and biceps</td>
<td>wrist supination</td>
</tr>
<tr>
<td>high</td>
<td>triceps</td>
<td>elbow extension</td>
</tr>
<tr>
<td>high</td>
<td>biceps</td>
<td>elbow flexion</td>
</tr>
<tr>
<td>high</td>
<td>triceps and biceps</td>
<td>wrist pronation</td>
</tr>
</tbody>
</table>

CONCLUSIONS

Several illustrations of the use of digital components and microcomputer technology in the design of some control systems for limb prostheses have been presented.

Extended clinical experiences with three below-elbow amputees indicates rate-sensitive three-state control to be an effective alternative to two-site control. The rate-sensitive circuit described offers proportional control over a wide dynamic range of EMG. The circuit is simple and realizable with few digital components. The authors believe that digital techniques will play an increasingly important role in the control of future limb prostheses, in the same way that these techniques are influencing so many other fields today.

We have demonstrated that the microcomputer is a powerful tool for empirical evaluation of various prosthesis control ideas. The laboratory trials have elucidated simple techniques for interfacing myoelectric signals with computers and have demonstrated how micro-computers may be used in future prostheses as all-purpose, generalized controllers.

REFERENCES

New three-state proportional myoelectric controller also shown in block-diagram form in Figure 3.

APPENDIX A

CAPACITOR VALUES ARE IN MICROFARADS

SINGLE-SITE MYO-PULSE AMPLIFIER

MC 108B

Note: 4-input NOR gates (4002) were used in the actual implementation as diagrammed above. However, the block diagram which appears as Figure 2 showed AND gates for descriptive purposes. With the AND gate configuration all inputs are required to go high before the gate output will go high. In contrast, NOR gate output goes high when all inputs go low except otherwise indicated.