Evaluation of Control Problems in Externally Powered Arm Prostheses

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More than a decade has elapsed during which limited research and development efforts on externally powered arm prostheses have been directed primarily toward solutions of associated technical problems. The major objective has been to provide the severely handicapped arm amputee with a prosthesis whose operation would require a minimum of physical effort for a maximum of functional replacement. Emphasis in the past was placed on technical components without giving due consideration to the total man-machine system. In this discussion we shall attempt to suggest a different approach, one oriented toward recognition of the need for comprehensive evaluation that includes the detailed problems of control and sensory feedback as well as the primary mechanisms of force and motion.

The rehabilitational value of any arm prosthesis is determined by the degree of accuracy and reliability with which the amputee can guide his prosthesis movements. Mechanisms that can effectively reduce the energy requirements of the amputee and also provide an adequate range of motion are well within current technological capabilities. Regardless of the excellence of the engineering design, however, none of the existing externally powered prostheses can be considered to be a fully satisfactory replacement of a lost arm. In the opinion of the authors, the current situation must be attributed in every case to the neglect of an evaluation of the capabilities and limitations of the control site and of the interactions of the wearer with the mechanism. Satisfactory function depends directly and fundamentally upon the adequacy of the control coupling in terms of the appropriate selection of mode of operation and site of actuation.

For any type of prosthesis two basic requirements must be satisfied by the control source: (1) It must show adequate physical signal characteristics with respect to transmission lags, phase, and sensitivity; and (2) It must provide the amputee with reliable sensory feedback for controlling the movements of the arm and terminal device.

From a review of past experience we find that a variety of body sites and transducer types have been utilized for controls. The choice of a particular control site has apparently been determined largely by the factors of easy accessibility for harnessing, and adequate motor output characteristics in terms of force and displacement.

Sensory feedback has received only secondary attention; it is largely by chance that adequate visual and force feedback have occurred in some models of conventional prostheses. Operation of the IBM-Alderson IV-E electric arm design for very short above-elbow stumps depended on an extremely complex system of nine spatially separated selector controls. For operation the amputee first had to select the correct switch for a given movement by blind "feel" with his stump on the inside of the socket. The next step was to "turn off" the switch after completion of the motion. Laboratory studies showed that the complexity of the control system, with respect to both physical signal characteristics and sensory feedback as well as the number of required decisions, was by far too great for satisfactory amputee performance.

A German development, the Heidelberg pneumatic prosthesis, is also equipped with a sequential control arrangement. In this case, the controls consist of a series of selector valves for power and function. After considerable training the amputee can achieve a certain level of reliable performance, but the performance is limited to a specific range of tasks, and control tends to break down under moderate stress conditions. Despite its shortcomings, the arm provides much greater function for extreme above-elbow amputation or shoulder disarticulations than any other development to date.

Both the IBM-Alderson arm and the Heidelberg arm employ a position-velocity control that produces a rate of movement by moving the control to a given spatial position. Such a control-action transfer is well known to require an excessive number of decisions on the part of the operator. Accordingly, in terms of good biotechnical engineering design the arrangement with both types of arms has been found to be unsatisfactory.

A unique contribution to the explicit recognition of the importance of sensory feedback is made in the French electric hand. Both a following-type position feedback and a force feedback are provided by back pressure on the pneumatic bladder actuator that controls prehension. The device is complex in electromechanical design and provides only prehension as an active function. The development is a significant contribution, however, as it has been fitted to many amputees and can provide a limited amount of laboratory information on feedback requirements.

Experience at the UCLA Biotechnology Laboratory with past developments and currently representative externally powered and conventional prostheses has enabled us to establish some criteria for an "ideal" control site. These criteria can be assigned to the three major categories of: (1) signal criteria, (2) noise criteria, and (3) coding criteria. Although the terms "signal," "noise," and "coding" are formally defined within the framework of information theory, they will be used only in a descriptive sense for the present purpose.

Signal Criteria

1. The signal output by the amputee must be reliable, clear, and unambiguous to the control signal pickup, i.e., a high signal-to-noise ration must obtain.
2. The signal should be capable of quantitative modification by the amputee over as wide a range of perceivable differential discriminations as possible.
3. The effect of the signal on the mechanism output must be free of transmission time lag in order to produce maximum error feedback to the senses of the operator.

Noise Criteria

1. A stable functional relation must be maintained between the control site and the signal pickup mechanism, independently of required arm loading and postural adjustments.

2. Operation of one control must not affect other control operations, i.e., there must be sufficient separation of controls to prevent inadvertant actuation of each control by the others.
3. Controls must be immune to actuation by environmental conditions such as vibration and electromagnetic radiation.
4. Controls must not induce "psychological noise," that is, the amputee should be free of discomfort, pain, and fatigue from proximity to the control signal pickup mechanism during periods of normal use.
5. Controls must be capable of effective function in relation to other features of the prosthesis, such as socket design and fit, stability of prehension, etc.

Coding Criteria

1. Coding of the relation between control action and its result should require a minimum of learning by the amputee; it should conform to population stereotypes for expected relations.
2. There should be close coupling between the discriminations made by the amputee at the control site and the magnitude of the mechanism action; the operator should act as a simple amplifier.
3. For maximum functional regain, integrated control actions as well as serial control actions that are coordinated in parallel should be possible, following the criteria for individual controls with emphasis on requiring a minimum of computing operations by the amputee.

For the purposes of developing actual equipment to achieve these somewhat idealized criteria, it seems reasonable to dichotomize the control site problem for externally powered prostheses into two categories of practical problems: (1) human (or "software") problems, and (2) hardware problems. The human factors that appear to be important are as follows:

1. Amputation level functional requirements
2. Control modes available
3. Number and location of control sites
4. Neuropsychological separation of controls
5. Multiple function coordination capability
6. Training
7. Site hygiene
8. Sensory feedback modes available
9. Sensory adaptation

At the present state of the art, the types of control modes available—namely, force and excursion from the muscles at relatively few body sites—are the most important limiting factor for further practical developments. It seems imperative to continue to direct major research efforts toward making new control modes available. The long term aim for significant advances seems to be achievement of neuropsychological separation of controls in order to provide the amputee with combination motions. Separation of controls may be attempted by various methods such as surgery, psychological conditioning, and electrical coupling, depending on the type of control modes that research makes available.

The associated hardware problems can be summarized as:

1. Type of control actuators and sensory feedback mechanisms
2. Weight
3. Size
4. Sensitivity
5. Reliability
6. Maintenance