Extended Physiological Proprioception for Electric Prostheses

L. E. Carlson & K. R. Primmer

ABSTRACT

The upper limb can be thought of as having two functional components: a grasping device (the hand) and a means to position the hand in space. Direct position control offers many advantages for controlling the latter task. Extended physiological proprioception (EPP), as developed in Scotland by Dr. David Simpson, has proved to be a very successful implementation of position control. Unfortunately, his system controls pneumatic prostheses as fitted in the United Kingdom, which are incompatible with the electric systems as fitted in the United States.

This paper describes an electrical version of EPP that is compatible with existing hardware. Various tracking and positioning tests demonstrate significantly improved performance over both conventional velocity control and position control without the feedback that is central to EPP. And, the system should prove to be inexpensive, compact, and reliable.

INTRODUCTION

An upper-limb prosthesis may be considered to have two distinct functional components: a grasping device and a means of positioning that grasping device in space. The latter is accomplished by motion of the amputee's residual limb, combined with prosthetic joint motions. The two functional components have different output variables; for grasp, force and velocity are of primary interest, while displacement is significant for positioning. Therefore, the two tasks may have different optimum methods of control.

Powered prosthetic joints usually employ velocity control for all functions in which the velocity of the joint is a function of the control signal. However, when the primary variable of interest is position, a better control strategy may be position control, in which joint position is a direct function of the control signal, capitalizing on the amputee's residual proprioceptive feedback.

CONTROL STRATEGIES

Whether it is controlled directly or indirectly, position is the ultimate variable of interest in controlling prosthesis motion. Velocity is of secondary importance since it is mainly concerned with enabling the amputee to position the prosthesis rapidly. Acceleration is less important since it cannot be appreciated by human controllers [1] and force, important in terminal device operation, is also relatively unimportant in joint motion.

Although velocity and acceleration are not primary variables of interest, they can be used to indirectly control prosthesis position. Naturally, each type of control has both advantages and disadvantages.

Position Control

Position control is the most straightforward control method. The output position (e.g., elbow angle, θ) is linearly proportional to the input signal, e, which may be a myoelectric signal or a relative body motion (Fig. 1). Velocity is then a function of the rate of change of the input signal, $\dot{e}$, which allows variable speed operation.

The main advantage of position control is the inherent feedback of prosthesis position. There is a one-to-one correspondence between prosthesis position and level of input signal; therefore, if the amputee can discriminate input signal level, he knows where the prosthesis will be without visual monitoring. If the input signal is relative body motion, then this information is available in very precise form as proprioception. Position control is very accurate [2] and natural, and time-optimal control is theoretically feasible [3].

The main disadvantage of position control is the necessity of maintaining an input signal level to maintain any position other than zero. However, this is precisely the way the normal musculoskeletal system functions, so it is probably not excessively demanding on an amputee, especially if only small forces are required.

Conventional dual-control cable-operated prostheses employ position control very successfully, except for large force and excursion requirements.

Position control is widely used in the United Kingdom, as described by Simpson [4], Lambert [5], McWilliam et al. [6], and others. In the United States, the Boston Elbow [7] initially utilized this method, as has the senior author [8].

Velocity Control

The simplest implementation of velocity control uses two control sites (e_1 and e_2) to move the prosthesis with constant velocity in either direction, or to keep it stationary in any position if the inputs are below a certain threshold (Fig. 2-a). Although widely used, this method has been shown to be too slow if it is kept stable [1]. Proportional control (Fig. 2-b) provides a range of speeds which allows faster, stable operation, but two control sites are still required. This scheme is commonly used in myoelectric systems.

Dorcas and Scott introduced the concept of three-state on-off control based on myoelectric signal amplitude in 1966 (Fig. 2-c) [9]. Their method requires only one control site to generate velocity in either direction, but the control is on-off. The commercially available VA elbow [10] is supplied with a three-state pull switch which functions in a very similar fashion (Fig. 2-d).

The three-state concept can be refined to allow proportional control in one direction, but on-off control in the other (Fig. 2-e). This can be used to advantage in controlling a prosthetic hand, where proportional control of closing velocity is very desirable to control prehension, but a constant opening velocity is quite acceptable [11]. However, it is often difficult to reliably maintain operation of the low level mode.

The rate-sensitive myoelectric circuit of Childress [11] (Fig. 2-f) appears to require less amputee concentration than purely amplitude-sensitive schemes. A slow, graded contraction causes proportional control in one direction (e.g., prehension), while a rapid contraction yields on-off control in the opposite direction.

Velocity control, regardless of the specific method, has the disadvantage of being non-physiological, since the amputee must integrate velocity to control position, so visual observation is required. A large dead zone is necessary to prevent inadvertent operation, and Freedy et.al. have shown that time-optimal control is not practically realizable [3]. The advantages are the fact that the prosthesis stops when the input ceases, and any position can be maintained without an input.

Extended Physiological Proprioception (EPP)

The most successful applications of position control to date have been the pneumatic total arm prostheses in Scotland developed by Simpson [12, 13, 14]. He has termed the control method "Extended Physiological Proprioception" (EPP), suggesting its unique way of extending the body's natural position feedback, proprioception, into the prosthesis.

As shown schematically in Fig. 3, EPP utilizes a transducer which can sense small relative position changes between the input link and base, actuating the prosthetic joint in the proper direction. A mechanical feedback link (cable or hydraulic) connected to the controlled joint moves the transducer base in the same direction, following the input motion. When the input ceases, this motion turns the joint off. Therefore, the system becomes a closed-loop servo that is, in Simpson's terms, "unbeatable," since the input is physically constrained to move only as fast as the prosthetic joint will allow. This mechanical feedback and interface is an essential element of EPP that provides the amputee with precise, direct knowledge of the position of the limb at all times.

A pneumatic elbow designed by the senior author also utilized EPP successfully [15]. Humeral flexion provided the actuation signal; proportional pressure valves, sensing an input signal, directed CO_2 gas to the cylinder to to flex the elbow. Therefore, the angle of the elbow was linearly related to the humeral flexion angle, providing feedback to the amputee both through proprioception in the shoulder girdle and reflection of the valve actuating force. The amputee had precise, smooth control of the limb in any position, and exhibited near-optimal motion patterns, even without visual feedback. Also, both rapid and slow motions could be made extremely smoothly.

EPP, then, is a demonstrably effective method to control the position of an upper-limb prosthesis. The one-to-one relationship between input and output position capitalizes on inherent neuromuscular feedback mechanisms to provide an extremely natural mode of control.

EPP FOR ELECTRIC PROSTHESES

For a variety of reasons, virtually all of the powered prostheses now available in the United States are electric, necessitating totally different hardware to implement EPP. Various types of sensors and feedback links were evaluated for suitability for the task. Sensors considered included piezoelectric elements, photodetectors, LVDT's, strain gages, strain elements (silastic tubing filled with mercury) and potentiometers.

A linearly actuated conductive plastic potentiometer proved to be the optimum choice. It is compact, inexpensive, and reliable. The resistance element and pick-up tab from a commercial slide potentiometer were removed from the potentiometer and built into a smaller package.

The feedback links considered were hydraulic and cable. While hydraulic links offer some advantages, mainly flexibility of the hydraulic line, the cost and possible leakage of hydraulics made cable feedback more attractive.

Using these components, a prototype was designed and constructed. The transducer, mounted at the control site and actuated by biscapular abduction, is shown in Fig. 4. Overall size of the transducer is approximately 11 X 4.5 X .7 cm.

The feedback link attaches to the transducer at one end and a cover mounted to the VA elbow at the other end. The only modification required to the elbow unit is the drilling of two holes to mount the cover. A pulley attached to the moving part of the elbow provides the feedback.

The transducer is excited by ±10.5 volts DC so that there is zero signal at null. The signal is amplified and fed to the elbow motor; a positive excursion generates a positive voltage (elbow flexion) while a negative signal causes extension.

PROTOTYPE TESTING

Two types of tests were performed in the laboratory with a normal subject: pursuit tracking and blind positioning. The tracking tests demonstrated a high level of precision not possible with velocity control.

Blind positioning tests were regarded as a true test of this concept. If EPP truly represents an improvement in positioning control, a subject should be able repeatedly to flex to a specified angle without visual cues. The results of such tests showed positioning repeatability within about 3°, compared to 16° for the same tests performed with the VA pull switch (Fig. 5). Auditory cues were the same for each type of control. This test performed with the feedback link disconnected yielded results in between these values, demonstrating the importance of feedback to the overall system. Fig. 5 also shows that EPP is a significantly smoother control, since the elbow slows to a stop as it approaches the set point rather than stopping abruptly.

Qualitatively, the system provided excellent control. Position and speed control were very smooth, reliable, and easy to learn. Overall, the results of these tests were very encouraging.

CONCLUSIONS

Extended Physiological Proprioception appears to offer significant improvements in positioning control of electrically-powered prostheses. It retains the advantages of dual-control body-powered systems but requires significantly less force and excursion to operate. Amputee evaluation of a smaller (5 X 1.8 X 1.3 cm) transducer is currently underway to further validate these conclusions.

References

1. Gavrilovic, M.M. and Maric, M.R., "An Approach to the Organization of the Artificial Arm Control," in Advances in External Control of Human Extremeties, Proc. of 3rd Int'l Symp. on External Control of Human Extremeties, Dubrovnik, Aug. 1969, pp. 307-322.

2. Case Western Reserve University, Final Report on Biomedical Research Program in Cybernetic Systems for the Disabled, EDC Report #4-70-29.

3. Freedy, A., Lucaccini, L.F. and Lyman, J., "Information and Control Analysis of Externally Powered Artificial Arm Systems," Bulletin of Prosthetics Research, 10-8, Fall, 1967, pp. 112-131.

4. Simpson, D.C. and Sunderland, G.D., "A Position-Servo Control System for Powered Prostheses," World Medical Electronics, 1965, 3:116

5. Lambert, T.H., "An Engineering Appraisal of Powered Prosthesis," J. Bone and Joint Surg. (Brit.), 49B, No. 2:333-341.

6. McWilliam, R., Montgomery, S.R. and Chapman, J.C., "Why Make Powered Artificial Arms?" New Scientist, Oct. 1969, pp. 182-184.

7. Ohlenbusch, C.W. and Russel, D.B., "An EMG Controlled Externally Powered Elbow Prosthesis," 20th Annual Conf. on Engng. in Medicine and Biology, Nov. 1967.

8. Carlson, L.E., "Multi-Mode Control of an Above-Elbow Prosthesis," D. Eng. Dissertation, Technical Report 61, Biomechanics Laboratory, University of California, Berkeley, Sept. 1971, 231 pp.

9. Dorcas, D.C. and Scott, R. N., "A Three-State Myo-Electric Control," Med. and Biol. Engng., 1966, 4:367-370.

10. Fidelity Electronics Sales Brochure; "Fidelity Electronics Externally Powered Elbow," Chicago, Ill., 1976.

11. Childress, D.S., Personal communication, 1970.

12. Simpson, D.C., "The Choice of Control System for the Multimovement Prosthesis: Extended Physiological Proprioception (e.p.p.)," Ch. 11, in The Control of Upper-Extremity Prostheses and Orthoses, Herberts et al., Eds., Chas. C. Thomas, 1974, pp. 146-150.

13. Simpson, D.C. and Kenworth, G., "The Design of a Complete Arm Prosthesis," Biomedical Engineering, Feb. 1973, pp. 56-59.

14. Simpson, D.C., "A Concept of Arm Function," Orthotic Practice, Edward Arnold Pub., 1976 (in press) 7 pp.

15. Carlson, L.E., "Closed-Loop Position Control of a Pneumatic Prosthesis," Proceedings of the 25th Annual Conference on Engineering in Medicine and Biology, October 1972, p. 97.

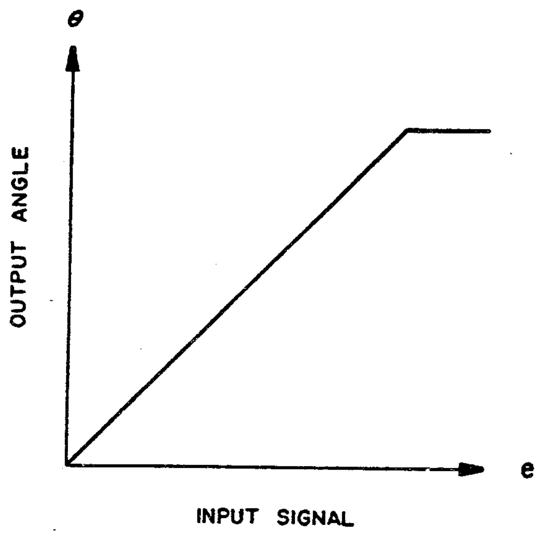
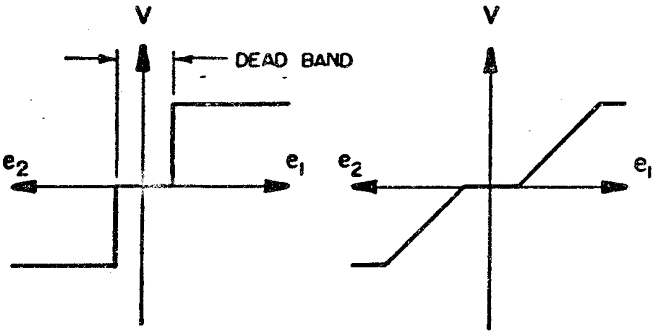
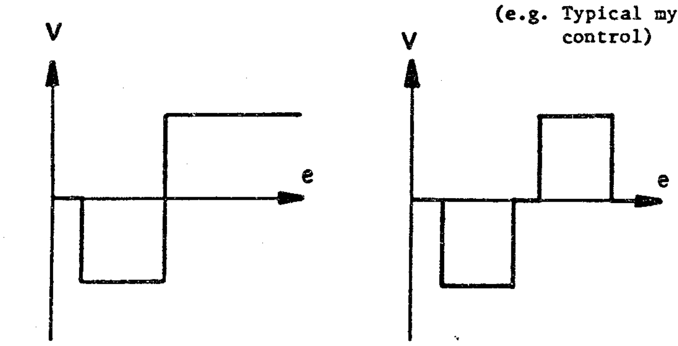


Fig. 1. Position Control. Output angle is linearly proportional to input signal level, which can be a relative body motion or myoelectric signal.



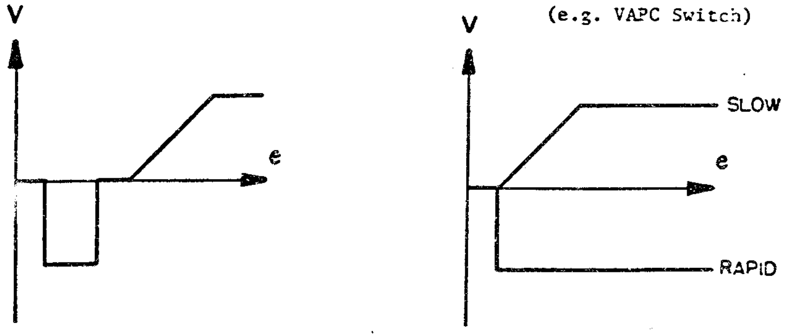
(a) Two-site on-off

(b) Two-site proportional
(e.g. Typical myoelectric control)



(c) One-site 3-state on-off

(d) One-site 3-state on-off with dead zones (e.g. VAPC Switch)



(e) One-site proportional/ on-off (amplitude sensitive)

(f) One-site proportional/on-off (rate sensitive)

Fig. 2. Velocity Control Methods

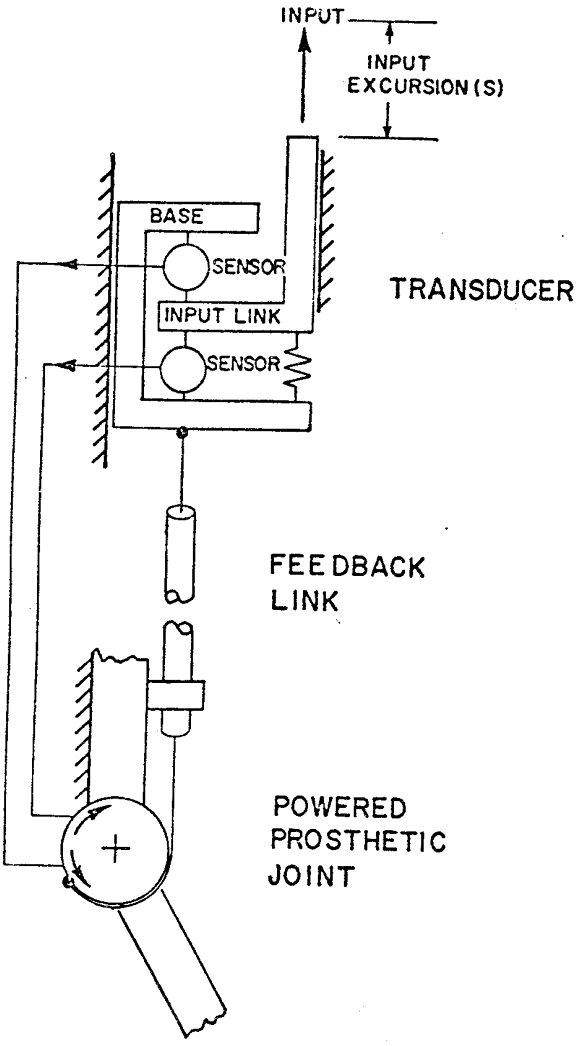


Fig. 3. Schematic of Extended Physiological Proprioception (EPP). An input displacement activates sensors which move the joint in the proper direction. The feedback link couples the transducer to the prosthetic joint.

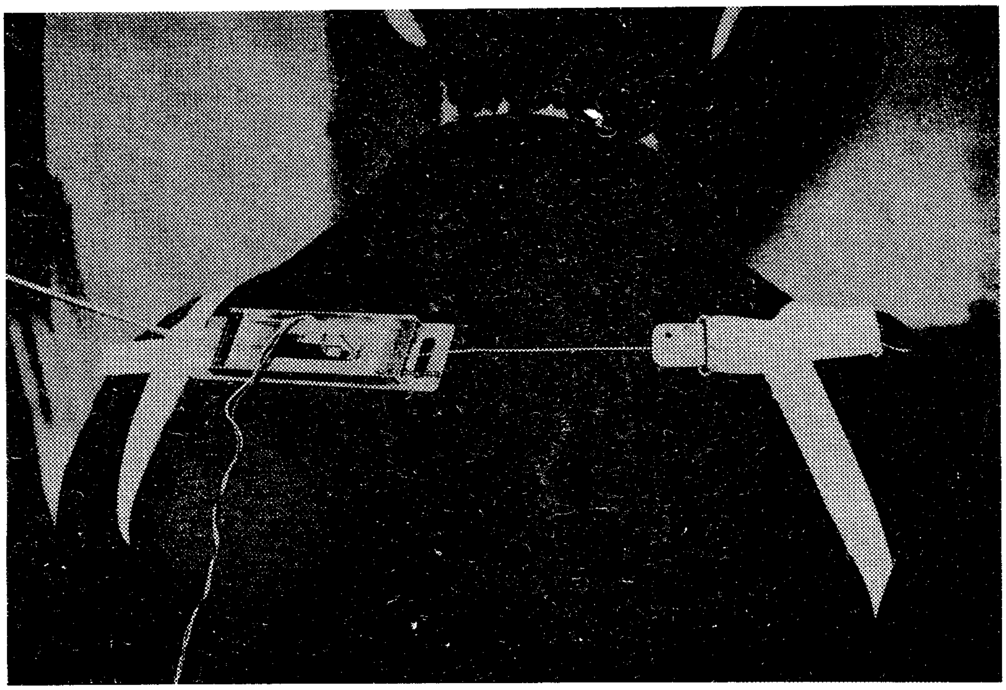
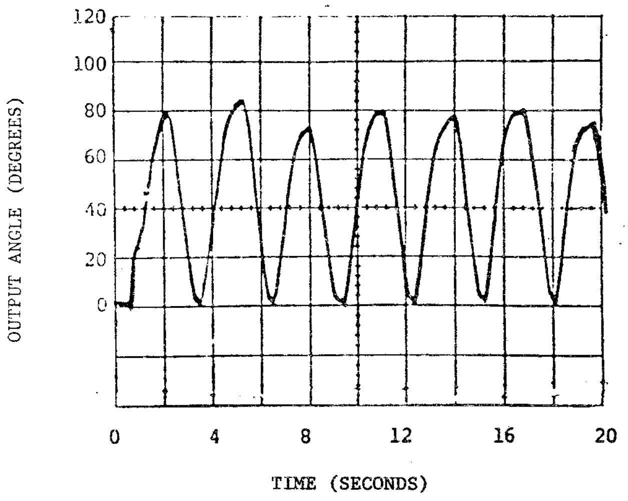


Fig. 4. EPP Transducer on a normal subject.



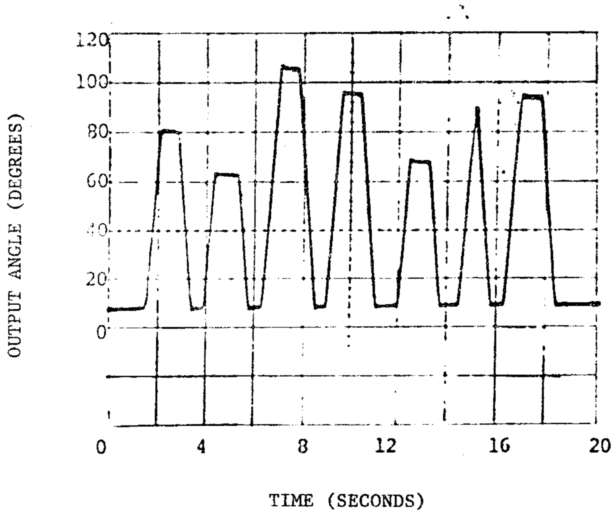


Fig. 5. Blind positioning tests. (Target angle: 80°).
Top: EPP System (position control).
Bottom: VA switch (on-off velocity control).