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An Analysis of Extended Physiological Proprioception as a Prosthesis-Control Technique

JAMES A. DOUBLER, Ph.D. [a]
DUDLEY S. CHILDRESS, Ph.D.

Prosthetics Research Laboratory
Northwestern University
345 East Superior Street
Chicago, Illinois 60611

Abstract— This research was devoted to an investigation of the practicality and potential effectiveness of applying the concept of extended physiological proprioception (EPP) to the control of upper-limb prostheses. The purpose of this study was to verify that EPP control, implemented by coupling prosthesis function to residual shoulder motion in a position-servo relationship, could be effectively applied in multifunctional prostheses for shoulder disarticulation amputees. Although Simpson has shown that the principle works, the authors wanted to quantify its effectiveness and analyze its limitations.

Studies were performed analyzing the feasibility of using shoulder elevation-depression and protraction-retraction as prosthesis control inputs. The results of this study showed that a prosthesis mechanism with nonlimiting dynamic response characteristics and shoulder-activated EPP control of wrist rotation and elbow flexion/extension, exhibited functional characteristics comparable to those of the physiological elbow and wrist as defined by tracking capabilities. The results of this investigation also showed that shoulder-effected position control of prosthesis function has considerably more potential for providing effective control than similarly effected velocity control.

INTRODUCTION

It is generally felt that prosthesis control can most effectively be implemented by providing a man-prosthesis interface in which the signals pertaining to prosthesis operation are coded in physiological terms natural to the residual sensory and neuromuscular systems of the amputated limb (Childress (1), Mann (2), Simpson (3), Jerard and Jacobsen (4)). With the ideal interface, prosthesis control would be effected by the part of man's physiological system most naturally associated with the function restored.

This paper presents the results of an investigation to quantify the effectiveness of applying the concept of extended physiological proprioception (EPP) to the control of upper-limb prostheses. Extended physiological proprioception can be realized in prosthetic control through the use of a control technique in which the modalities of information-transfer across the man-prosthesis interface are similar to those associated with the control of the natural limb. The representation of motor intent by the amputee involves the same mental processes used in the control of the natural musculature, and proprioceptive and envi-

[a] Now with AT&T Bell Laboratories, Naperville, Illinois.

ronmental sensations are presented to the amputee in a naturally perceived manner. In undertaking this study it was hypothesized that EPP control has significant advantages for achieving effective and natural control of upper-limb prostheses, particularly in multifunctional applications. The purpose of this study was to gather data that would allow assessment of the advantages of the approach and that could reveal the potential of the control method. Practical applications have been indicative of its effectiveness but the authors wanted to conduct studies that investigated the approach in a quantitative manner.

EXTENDED PHYSIOLOGICAL PROPRIOCEPTION (EPP)

Conceptual Basis for EPP

The concept of extended physiological proprioception was formalized and proposed as a prosthesis control technique by D.C. Simpson (3,5), who reduced the concept to clinical practice in an elegant series of CO_2-powered prostheses for children. It implies that the manner in which a mechanical device is controlled or used can be such that the operator is able to perceive its static and dynamic characteristics through naturally arising proprioceptive sensations. By eliciting proprioceptive sensations, the device becomes an artificial extension of the operator, part of the functioning person. The feedback information may be fundamentally important in itself or important as a means of monitoring the activity of the device.

The manner in which a blind person uses a cane as a mobility aid is an excellent illustration of this concept. Information about the environment is coded in proprioceptive sensations arising in the extremity supporting the cane. Although transmitted by the cane, these sensations do not pertain only to the nature of the cane, but rather serve to describe aspects of the nature of the environment. Thus the cane serves as an extension of the blind person's existence, shifting outward the point at which contact is made with objects external to the person's being.

Another demonstration of extended physiological proprioception can be seen in the way a tennis player controls his racket. The position, velocity, and acceleration of the racket in space are directly related to the nature of the player's grip and the motion of his arm, information about which is available as proprioceptive sensations. As the player learns to associate this proprioceptive information with the dynamic aspects of racket performance, control of the racket becomes reflexive and subconscious.

EPP in Prosthesis Control

Simpson proposed that extended physiological proprioception could be realized in the control of externally powered prostheses by coupling prosthesis function to residual joint motion in a position-servo relationship where the input cannot 'beat''the output. With such a system, the position and movement of a prosthesis joint are at all times directly related to the position and movement of an anatomical joint, the anatomical joint being physically constrained to maintain a constant relationship between it and the prosthesis. The system is a position servomechanism in which the input is physically constrained by the output so that the input cannot get ahead of or fall behind the output, even temporarily.

With this control system, the modalities of the information pertaining to operation in both the forward and feedback control paths are similar to those associated with the control of the natural limb. By intimately linking the physiological joint position to the prosthesis joint position, the proprioceptive feedback mechanisms related to the control of the physiological joint may be directly associated with the operation of the prosthesis joint. As noted by Simpson (3), it seems unlikely that a more effective means can be found of communicating information pertaining to joint function to a person than by the physiological proprioceptive mechanisms. This inherent wealth of feedback information pertaining to operation is the primary factor that sets EPP control apart from the other approaches to prosthesis control.

While the preceding discussion has centered on the important feedback aspects of EPP control, it is also important to emphasize the appropriateness and potential effectiveness of the forward control path in such a system. Since the prosthesis joints are linked directly to physiological joints, the user generates motor commands to control the prosthesis that are similar in kind to those he would generate to control the physiological limb it replaces. This relationship takes on added significance relative to a fundamental hypothesis in motor control theory, which states that coordinated movements are not represented in the higher levels of the central nervous systems as joint-muscle schemata, but rather exist as topologically oriented engrams that can be translated into different joint-muscle sets (Bernstein (6)). For EPP control, this hypothesis implies that the prosthesis user would be able to naturally translate the control engrams for coordinated movements formerly performed by the missing extremity into topologically comparable movements of the joints now controlling pros-

thesis function. The prosthesis movements would therefore also exhibit the same topological organization, scaled by the EPP control mapping relationship between physiological joint input position and prosthesis joint output position.

Previous Implementations

Conventional cable-operated prostheses embody the concept of EPP control to a certain extent, particularly those for below-elbow amputees. The direct mechanical linkage between input and output provided by the Bowden control cable in below-elbow systems yields a position-servo type of relationship. A significant amount of feedback information that can be directly related to terminal device function is available to the amputee through proprioceptive and sensory input derived from cable operation and harness and socket pressures. Much of this direct feedback is lost, however, in prostheses for above-elbow and shoulder disarticulation amputees.

Simpson and co-workers (7,8,9) applied EPP control in upper-limb prostheses for children with thalidomide-induced bilateral amelia. They felt that one really effective prosthesis provided bilateral amputees with more useful function than two lesser systems. Acting on this premise, they developed a pneumatically-powered arm in which the positions of the two clavicles were used to control up to four degrees of freedom in a position-servo relationship. The four degrees of freedom included three polar coordinates specifying terminal device placement, and a rotational coordinate for terminal device orientation. If the actuator were restrained from moving, the corresponding clavicular movement was also restrained, maintaining shoulder position constant relative to the prosthesis. In that way, proprioceptive information derived from the shoulder girdle could always be accurately related to prosthesis operation. It was reported that the children who used those prostheses achieved a considerable degree of subconscious control and position awareness of the limb.

Carlson (10) applied EPP control to a pneumatically-powered elbow in a prosthesis for above-elbow amputees. In that system, the angle of elbow flexion was linearly related to the angle of humeral flexion. Carlson and co-workers (11,12) also developed an EPP controller for an electric elbow; with this system, elbow flexion was coupled to biscapular abduction. Excellent results were reported from laboratory tests of both systems. Smooth and precise control of prosthesis position and movement was reported, even with vision occluded.

INVESTIGATION OVERVIEW

It was originally hypothesized that EPP control derived from residual shoulder motion could be effectively applied in multifunctional prostheses for shoulder disarticulation amputees. To check this hypothesis, an investigation was performed analyzing the feasibility of using shoulder elevation-depression and protraction-retraction to control elbow flexion and wrist rotation in such a prosthesis.

As the initial step in the investigation, the ability of normal subjects to control physiological elbow flexion-extension and wrist pronation-supination was analyzed based on the performance in one-dimensional and two-dimensional random tracking experiments. Accepting the premise that the ultimate prosthesis will exhibit functional characteristics comparable to those of the natural limb it replaces, the results of these experiments served as optimal prosthesis-performance parameters.

Next, a study was performed analyzing the ability of subjects to control physiological shoulder elevation-depression and protraction-retraction as prosthesis control inputs. For this study, subjects performed one-dimensional and two-dimensional random tracking experiments using shoulder-effected position and velocity control of the tracking follower. Assuming a prosthesis with non-limiting dynamic characteristics that responds instantaneously to the control inputs, the results for shoulder-effected position control provide an indication of the performance that could theoretically be realized with EPP control. The tracking results for shoulder-effected velocity control allow a comparison to be made between the relative effectiveness of velocity control and EPP control.

After completing the hypothetical analysis, an experimental prosthesis was built for further evaluation of the concept and principles of EPP control. The experimental prosthesis utilized a shoulder-motion transduction mechanism in which direct cable linkages to the prosthesis components were used to implement EPP position-servo relationships between shoulder elevation-depression and prosthesis elbow flexion, and between shoulder protraction-retraction and prosthesis wrist rotation. The experimental prosthesis was evaluated by non-amputee subjects performing experimental tasks similar to those performed in the previous studies. In evaluating the prosthesis, task performance using EPP control was compared to that for velocity control of the same mechanism, and also to task performance by subjects using their physiological upper-limb.

The remainder of this paper is devoted to a

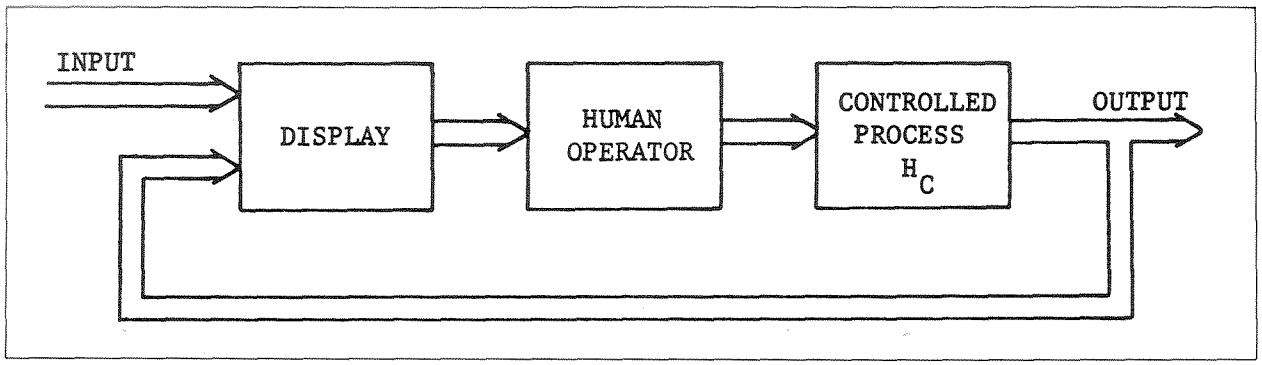

FIGURE 1
Schematic representation of pursuit tracking system of the type used in this study.

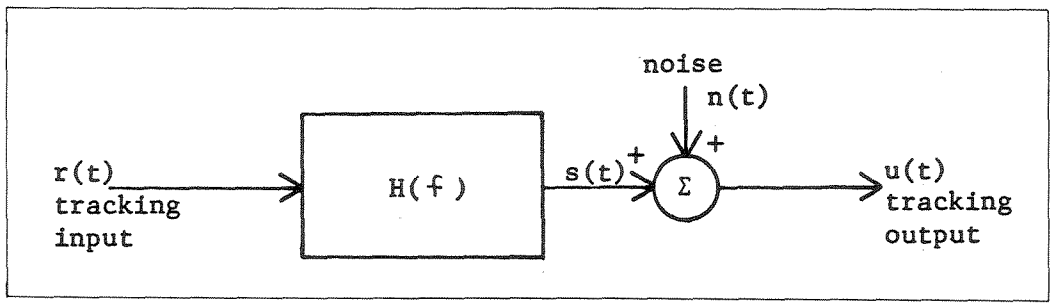

FIGURE 2
Quasi-linear representation of tracking system.

discussion of the methods and results of the studies performed in analyzing the ability of subjects to control their physiological arm and shoulder. The design and evaluation of the experimental prosthesis are detailed in a companion paper by Doubler and Childress (13), also presented here.

ANALYSIS METHODS APPLIED IN THIS STUDY

To predict and analyze accurately the potential effectiveness of a prosthesis-control technique, parameters must be specified for evaluating performance. The goal in prosthesis design is to provide a system that achieves the maximum restoration of function while minimizing the conscious attention to control required. Yet concentration on the control task being attempted is an inherent aspect of almost all laboratory analyses of prosthesis function. It seems reasonable to assume, however, that the ability to control a prosthesis while directly attending to it does provide some indication of the potential for subconscious control. Thus it should be possible, through careful consideration of the control philosophy employed, to perform a laboratory analysis that provides a confident indication of real-world potentials.

In this investigation, extensive experiments were performed analyzing the ability of subjects to control their upper-limb and prosthetic replacements, based on the performance of pursuit tracking tasks with continuous random input signals. A pursuit tracking system, represented schematically in Figure 1, was utilized because it was felt to be the type of manual control system that best represents the characteristics of upper-limb control and function while also providing a tractable and easily understood representation of performance. For some time it has been known that when the input appears random, the input-output relationship for a pursuit manual control system can be represented by a linear element—whose characteristics remain constant as long as the input characteristics and task variables remain constant—in series with a source of random noise, as shown in Figure 2 (see e.g. Elkind and Forgie (14)). Because of the dependence of the linear parameters on task variables, this representation is designated a "quasi-linear" model. The advantage of this representation is that because task variables are maintained constant during analysis, linear control theory techniques can be used to analyze and describe system operation.

Several linear parameters, such as the system transfer function and input-output coherence function, were initially derived and studied in searching for a meaningful and straighforward representation of control performance. One linear parameter that seemed particularly relevant to this study was derived by noting that the system model given in Figure 2 is precisely the same as that for an information channel with additive noise. For continuous random tracking experiments, the subject's task is to produce a signal at the system output that matches the input as closely as possible. This

task can be considered analogous to transmitting the input information across the channel with as little error as possible.

Shannon (15) showed that the channel capacity (maximum rate at which information can be transmitted) of a continuous channel of bandwidth W perturbed by white Gaussian noise of power N is given by

$$C = W \log_2 (1 + S/N) \qquad [1]$$

where S is the average transmitter power and C is expressed in bits/sec. He further showed that, to achieve this capacity, the transmitted signals must have a Gaussian amplitude density and flat frequency spectrum over W. In the case where the signal-to-noise ratio (S/N) is not constant over W, this relationship can be generalized by considering small slices of the frequency spectrum over which a constant signal-to-noise ratio can be assumed. Taking this process to the limit, the maximum information transmission rate, $\dot{T}$, is given by

$$\dot{T} = \int_W \log_2 \left[1 + \frac{S(f)}{N(f)} \right] df \qquad [2]$$

This relationship can be experimentally calculated using the relationship

$$1 + \frac{S(f)}{N(f)} = \frac{\Phi_{uu}(f)}{\Phi_{uu}(f) - [H(f)]^2 \Phi_{rr}(f)} \qquad [3]$$

where Φ_{rr} and Φ_{uu} are the input signal and output signal power spectra, respectively. Note that H(f) for the system in Figure 2 is given by

$$H(f) = \frac{\Phi_{ru}(f)}{\Phi_{rr}(f)} \qquad [4]$$

where Φ_{ru} is the cross-power spectrum relating the system input and output.

As far as is known, information transmission analysis of this kind has not been used previously in studying and comparing upper-limb function and prosthesis control. The effectiveness of prosthesis control is in large part determined by how well the user can communicate his motor intent to his prosthesis; based on that premise, information transmission is a concept philosophically aligned with this analysis of prosthesis system performance.

ANALYSIS OF PHYSIOLOGICAL CONTROL OF THE UPPER EXTREMITY

As noted previously, the purpose of this analysis was to determine the effectiveness of physiological shoulder motion as prosthesis control input. To achieve this purpose, one- and two-dimensional random tracking experiments were performed using three different kinds of control: (i) tracking with physiological elbow and wrist motion, (ii) tracking with shoulder-effected position control, and (iii) tracking with shoulder-effected velocity control.

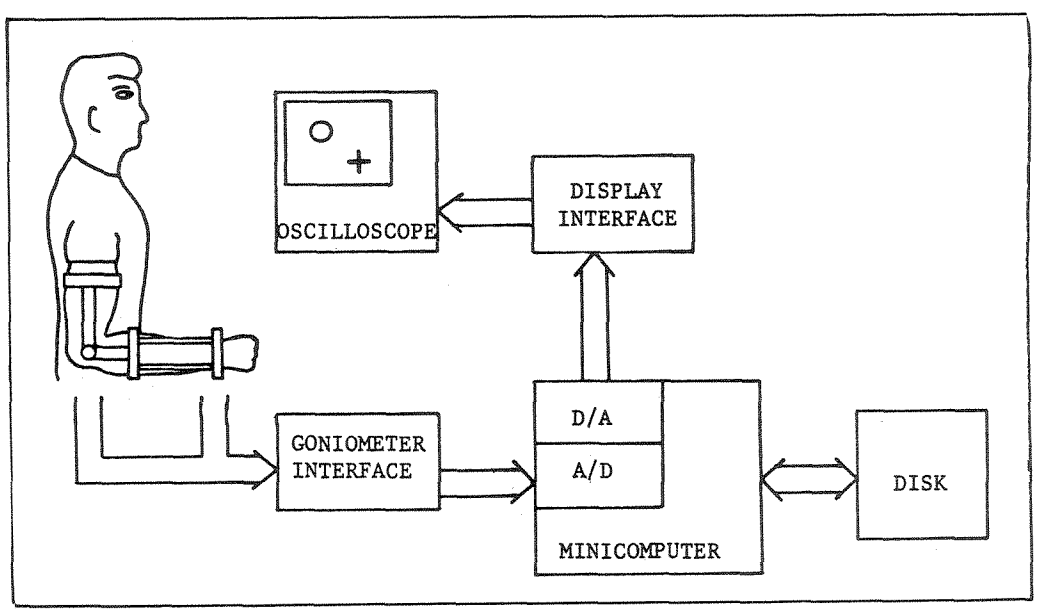

FIGURE 3
Block diagram of experiment control and data acquisition system.

Three healthy males in their mid-20's served as subjects in the experiments for tracking with the physiological elbow and wrist. Two healthy males in their mid-20s served as subjects in the experiments for tracking with shoulder-effected position and velocity control.

Experiment Control and Data Acquisition System

A minicomputer-based experiment control and data-acquisition system was utilized in the experiments performed in this study. (A block diagram of the system is shown in Figure 3.) In the experiments, the subjects interacted with an oscilloscope display on which a circle and crosshair were presented. The X and Y display coordinates of the crosshair were specified by the outputs of goniometers attached to the subject's upper-limb. The position of the circle indicator served as a target for desired joint position, its position in one or two dimensions being determined by computer-generated signals.

Goniometric Systems

Two different goniometric systems were used in these experiments. One system allowed simultaneous measurement of elbow flexion-extension and wrist pronation-supination in the right arm. The elbow goniometer in this system consisted of two single-axis hinges (one instrumented with a potentiometer) attached to cuffs around the humerus and forearm. The system's wrist goniometer was derived from a potentiometer-instrumented wrist rotation unit originally used in a powered orthosis. The lengths of the humeral and forearm sections of the goniometric system could be adjusted to fit different subjects.

The other goniometric system, used to measure shoulder movement and position, consisted of a potentiometer-instrumented linkage with two degrees of freedom, positioned over the sternoclavicular joint and connected by a rigid rod to another linkage positioned over the acromion process. Each subject wore a custom-fitted plastic body-jacket to which the sternoclavicular linkage was rigidly attached and held in place. The acromion linkage was attached to a small shoulder cap held in place against the skin by double-sided tape and a strap through the axilla. The linkages were positioned in such a way that, during shoulder movement, the connecting rod remained approximately parallel to the clavicle, and the two potentiometers in the sternum linkage provided measures of clavicular motion in the frontal plane (elevation-depression) and in the transverse plane (protraction-retraction), respectively.

Display Gain Relationships

With each goniometric system, an electronic interface was used that provided output signals linearly related to measured joint angle. During experiments, those signals determined the position of the tracking follower.

For tracking with the physiological elbow and wrist, the position of the crosshair indicator along the X-axis of the display was linearly related to the output of the goniometer measuring wrist position. Follower position along the display Y-axis was linearly related to the output of the potentiometer measuring elbow position. The gains of the goniometer and display interfaces were set such that angular displacements of 40 degrees of the elbow and wrist yielded follower displacement of 1 inch (2.54 cm) along the corresponding axis.

For tracking with shoulder-effected control, the position of the crosshair follower along the display Y-axis was determined by the output of the goniometer measuring shoulder elevation-depression and follower position along the X-axis was determined by the output of the goniometer measuring shoulder protraction-retraction. Follower position along the X and Y axes was linearly related to the outputs of the respective goniometers.

Initially, experiments were performed in which it was assumed that the full range of desired prosthesis motion (180 degrees of wrist rotation and 130 degrees of elbow flexion) was mapped into the full range of shoulder motion. Based on that concept of prosthesis control, the gains of the goniometer and display interfaces were set such that, for each subject, shoulder movement through the full range of elevation-depression (30–40 degrees) yielded displacement of the displayed follower equivalent to that yielded by 130 degrees of elbow flexion-extension movement in the tracking experiments performed with the physiological elbow. Similarly, shoulder movement through the full range of protraction-retraction (approximately 40 degrees) yielded crosshair displacement equivalent to that yielded by 180 degrees of wrist rotation.

Random tracking experiments were also performed in which the full range of theoretical prosthesis movement was mapped into ½ of the full range of shoulder movement.

For shoulder-effected velocity control, the velocity with which the tracking follower moved along the display X and Y axes was linearly related to the outputs of the respective goniometers. The shoulder-position/follower-velocity gain relationship was important in these tracking ex-

periments. If the gain was too low, the follower could not be made to move fast enough for accurate tracking of the target. If the gain was too high, stable control of follower position was difficult and the output tended to oscillate.

For these experiments, the gain relationships used were determined empirically by allowing each subject to choose the relationship that felt the most responsive, yet stable. The actual gain relationships (in terms of follower-movement velocity on the display screen per degree of goniometer displacement) chosen by the two subjects who performed these experiments were 0.67 and 0.85 in/sec/deg (1.70 and 2.16 cm/sec/deg), respectively. Based on the maximum excursion ranges measured, the absolute maximum movement-velocities achievable were approximately 14 in/sec (35.6 cm/sec). If it is hypothesized that the shoulder movements are being used to control highly responsive prosthesis joints whose positions in turn specify the position of the tracking follower, this corresponds to a theoretical maximum joint velocity of about 10 rad/sec.

Tracking Input Signals

During experiments, the position of the displayed circle target was controlled by "random" input signals stored in computer memory. These lowpass signals were generated by amplifying, sampling, and digitally filtering Zener diode shot and thermal noise at 8 different cutoff frequencies (0.16, 0.24, 0.40, 0.64, 0.96, 1.36, 1.84, 2.40 Hz). The signals had Gaussian amplitude distributions and flat power spectra below the cutoff frequency, rolling off at -200 dB/dec above the cut-off frequency. A total of 40 random input signals were generated, 5 for each cutoff frequency. Owing to the nature of their generation, all of these signals were uncorrelated.

The filtered input signals were scaled so that each had an rms amplitude of 1.46 V regardless of cutoff frequency. The X and Y axis display interface gains were set at 4 V/in (1.57 V/cm). As noted previously, for tracking with the physiological elbow and wrist, joint displacement of 40 degrees yielded follower displacement of 1 inch (2.54 cm).

Procedure for Random Tracking Experiments

In these experiments, for each control condition the subjects were required to perform three different random tracking tasks: (i) one-dimensional tracking of target motion along the display X-axis, (ii) one-dimensional tracking of target motion along the Y-axis, and (iii) two-dimensional tracking of target motion in the X-Y plane.

For the experiments, the subjects were seated 2 feet (0.61 m) from the display. A single tracking run lasted 2 minutes. For each control condition, the subjects performed 5 runs of each tracking task for each of the eight different frequency classes of input signals. To prevent the subjects from becoming familiar with the characteristics of the input signal, different signals were used for each of the 5 runs. However, to eliminate the possibility of performance differences attributable to statistical variations, the same input signals were used for each of the three different tasks and for the different control conditions.

In the 5 runs for each two-dimensional task, the same 5 uncorrelated input signals were used to control the X coordinate of the displayed target as were used to control the Y coordinate. However, the signals were used in different order. Thus over the 5 runs, the characteristics of target motion in both the X and Y directions were precisely the same, but the relative motions along the two axes were uncorrelated.

All the runs for one class of inputs, i.e. 5 for each task, 15 total, were performed in a single sitting. Sufficient time was provided between runs to avoid subject fatigue. The one-dimensional tasks were always performed before the two-dimensional task, alternating the order of one-dimensional X-axis and Y-axis tracking in subsequent sittings.

Subjects were instructed to follow target position as closely as possible, keeping the follower centered in the target if they could. They were given no learning period. However, the tracking tasks were performed first for the lowest-frequency input signals, with the higher-frequency inputs being presented in order of increasing cutoff frequency. This meant that by the time the higher-frequency inputs were in use and tracking had become difficult, the subjects had acquired considerable experience with the procedure.

The data for each set of 5 tracking runs performed for each tracking task and input-frequency class were stored in computer memory and combined in a single 10,240-point file representing approximately 8.5 minutes of tracking data sampled at 50 msec intervals. For two-dimensional tasks, two files were generated, one for the X-axis tracking component of the response, the other for the Y-axis component.

The tracking data files were first analyzed with the appropriate input signal files to obtain input power, output power, and cross-power spectra.

The power and cross-power spectra were derived by separating the data files into ten 1024-point segments, computing the spectrum for each segment using Fast Fourier Transform (FFT) techniques, and averaging the results. This method, called averaging periodograms, is equivalent to that proposed by Welch (16).

The resulting spectra were used to derive the quasi-linear system transfer function via a straightforward discrete frequency representation of Equation [4]

$$H(f_k) = \frac{\Phi_{ru}(f_k)}{\Phi_{rr}(f_k)} \qquad [5]$$

The maximum information transmission rate was then derived using Equations [2] and [3] and summing the frequency components within the passband of the input signal. The precise relationship used was

$$\dot{T} = \frac{1}{NT} \sum_{k=\phi}^{K} \log_2 \left[\frac{\Phi_{uu}(f_k)}{\Phi_{uu}(f_k) - [H(f_k)]^2 \Phi_{rr}(f_k)} \right] \qquad [6]$$

where N=the number of data samples in a segment, T=the sample interval, $f_k = k/(NT)$ and $K/(NT) \leq f_c$, the input signal cutoff frequency. As noted previously, for this study N=1024 and T=50 msec.

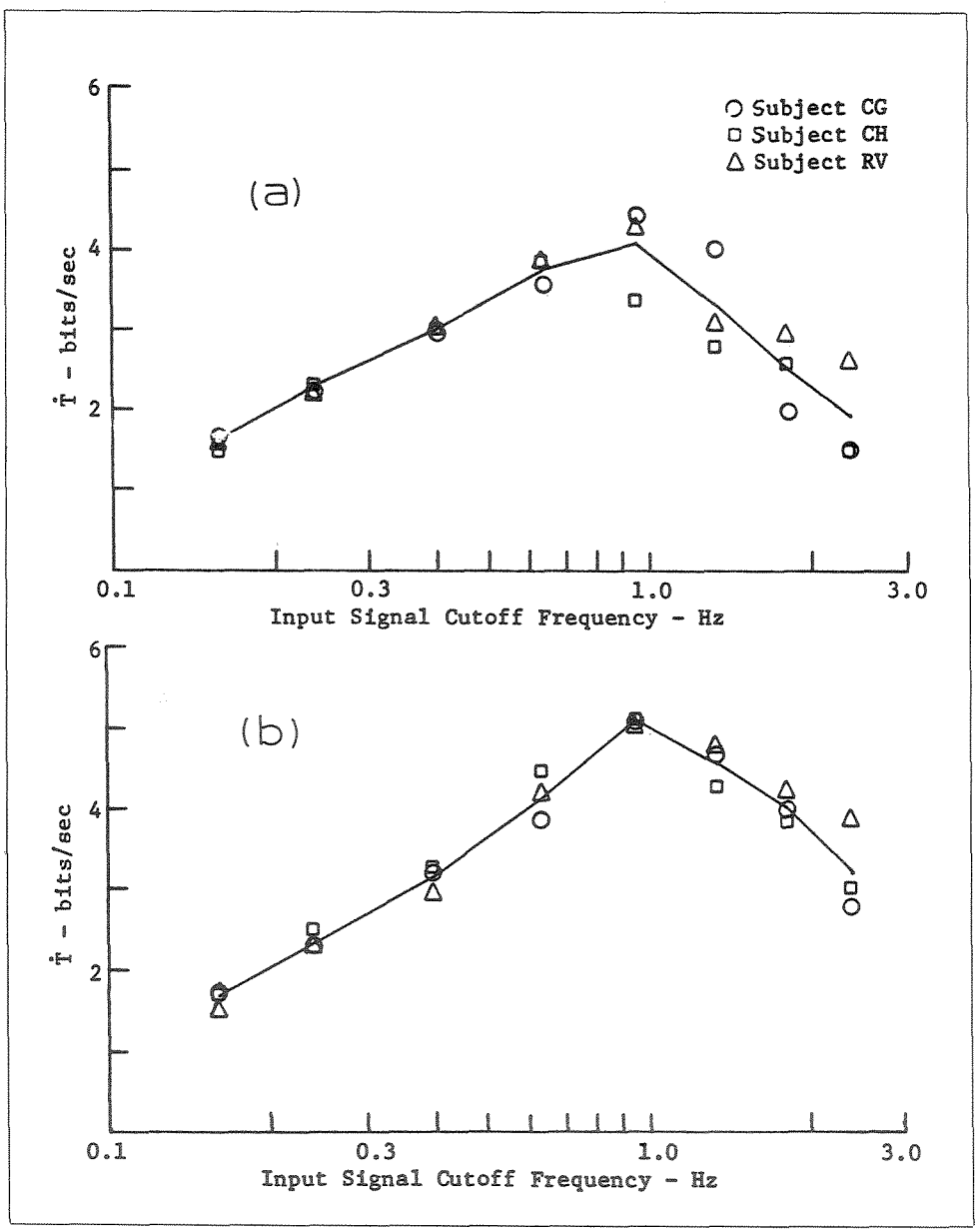

FIGURE 4
Information transmission rates as a function of input signal cutoff frequency for one-dimensional tracking with the physiological elbow (a) and wrist (b).

Experimental Results

A detailed presentation of the data obtained from these experiments is beyond the scope of this paper (see Doubler (17) for a more in-depth discussion). The following discussion centers on the results most relevant to the specific topics addressed in this paper.

Examples of the maximum information transmission rates obtained for one-dimensional tracking with the physiological elbow and wrist are shown in Figure 4. The results are similar to those reported by Elkind and Sprague (18) for pursuit tracking with a hand-operated joystick. For the lower-frequency input signals, the subjects were able to track the target accurately. Thus the response signal-to-noise ratio remained generally constant, and there was an approximately linear increase in the information transmission rate with increasing input-signal cutoff frequency.

The information transmission rates achieved generally peaked for input signals with cutoff frequencies near 1 Hz. As the input-signal cutoff frequency increased above 1 Hz, tracking became increasingly more difficult and the signal-to-noise ratio of the responses decreased rapidly, causing the observed decrease in information transmission rate. The inability of human subjects to accurately track random input signals that have significant energy above 1 Hz is a recurring finding in the literature on manual control.

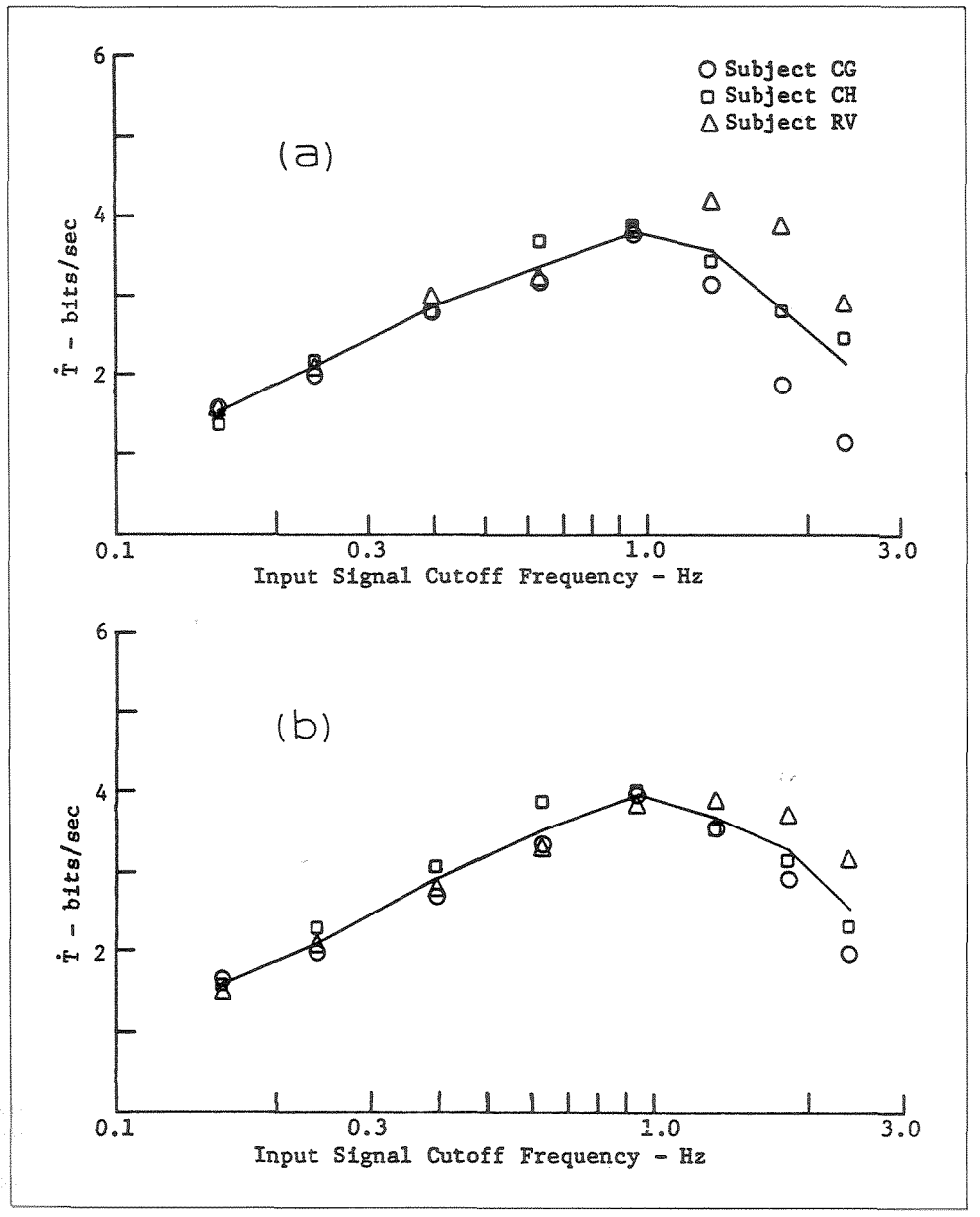

FIGURE 5
Information transmission rates for tracking with the physiological elbow (a) and wrist (b) in two-dimensional tasks. These data were derived by separating the two-dimensional response into the components corresponding to elbow and wrist tracking.

As can be seen in Figure 4, the data indicate that the subjects were able to track somewhat more effectively with wrist movement than with elbow movement. It seems likely that this difference in tracking capabilities is primarily due to the increased inertial loading associated with elbow movement. It is probable that improved high-frequency tracking performance for the elbow could be realized with smaller-amplitude input signals.

Two-dimensional tracking performance was analyzed by separating the two-dimensional responses into the components derived from the individual control inputs. As discussed earlier, the two signals controlling target motion along the X and Y axes in two-dimensional tasks were uncorrelated. Therefore the portion of each output signal that was linearly related to each of the inputs could be precisely specified.

Examples of the results obtained for two-dimensional tracking with the physiological elbow and wrist are shown in Figure 5. Comparing Figures 4 and 5, it is not surprising to see that wrist tracking was apparently significantly better when performed independently than when performed simultaneously with elbow tracking. Note, however, that while for low-frequency inputs subjects did attain slightly higher information transmission rates for independent elbow tracking than for simultaneous elbow tracking, the situation was reversed for the higher-frequency inputs. These results reinforce the theory that the difference between elbow and wrist tracking performance can be linked to the increased inertial loading associated with elbow movement. The increased mental effort required for two-dimensional control evidently had little effect on elbow tracking performance, indicating

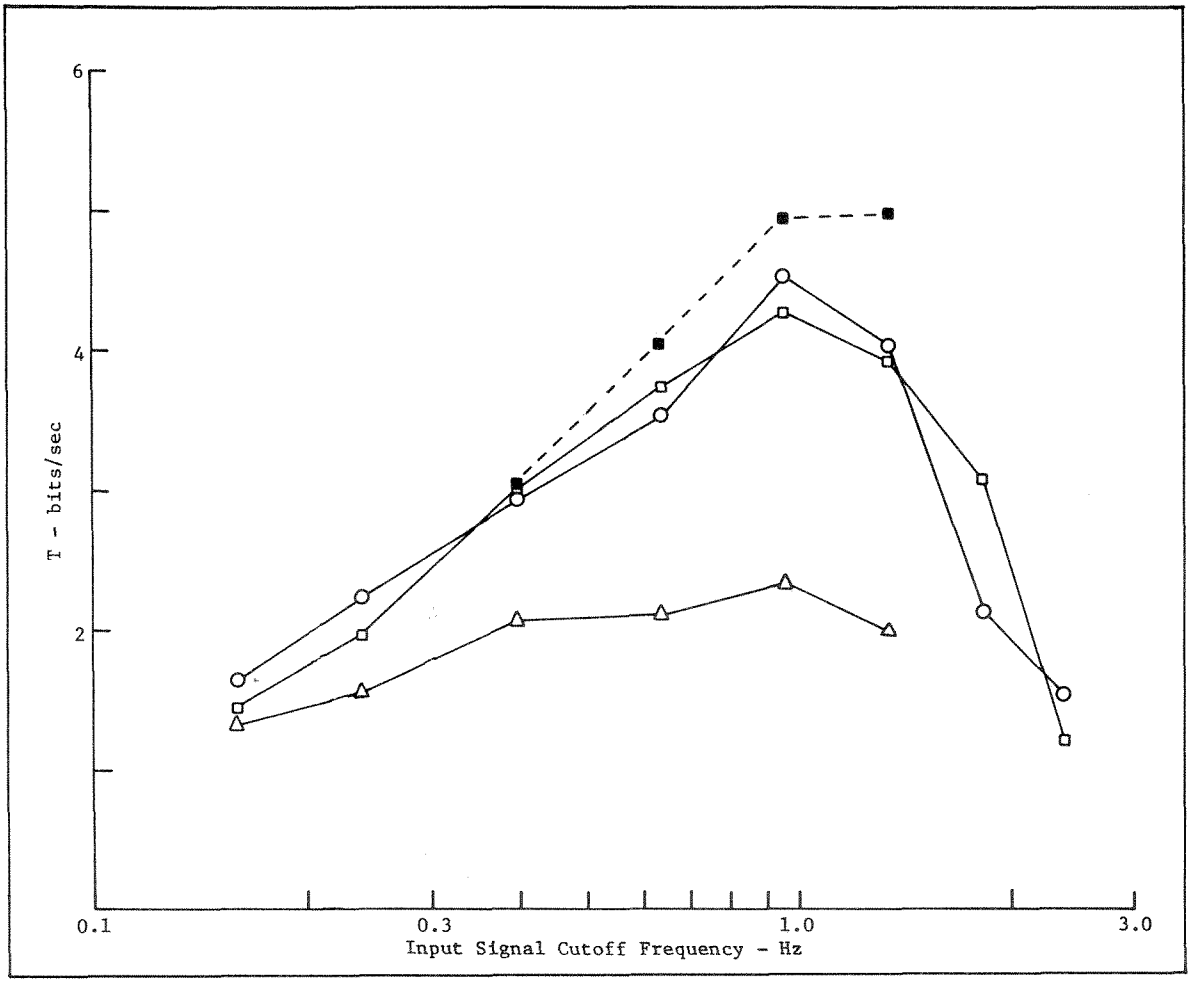

FIGURE 6
Comparison of the information transmission rates for one-dimensional tracking tasks performed by the same subject with the physiological elbow and with shoulder-effected position and velocity control using shoulder elevation-depression.

○ Physiological elbow
□ Shoulder-effected position control (initial gain)
■ Shoulder-effected position control (increased gain)
△ Shoulder-effected velocity control

some other limiting factor. The differences observed are small and it seems reasonable to assume that they may have arisen through the adopting of different tracking tactics by the subjects.

Qualitatively, the results obtained for shoulder-effected position-controlled and velocity-controlled tracking were similar to those for tracking with the physiological elbow and wrist. As before, the peak information transmission rates were achieved for input signals having a cutoff frequency of approximately 1 Hz. The data indicate that subjects were able to track somewhat better with shoulder elevation-depression than with protraction-retraction, although the difference was not particularly large. Note that shoulder motion of the type required in these experiments is somewhat unnatural, since persons are seldom required to perform isolated shoulder movements of the kind required in these experiments in normal situations.

Again, as for the physiological elbow and wrist, comparison of the results for one-dimensional tracking with those for two-dimensional tracking indicated that for shoulder-effected position and velocity control, performance for each control input was generally better when performed independently than when performed as part of a two-dimensional task.

The fundamental objectives of this investigation were to (i) determine the potential effectiveness of using shoulder motion as the control input for an EPP controlled prosthesis, and (ii) compare the relative effectiveness of shoulder-effected position and velocity control. In Figures 6 and 7 the information transmission rates for one-dimensional tracking with the different control conditions are plotted as a function of input signal cutoff fre-

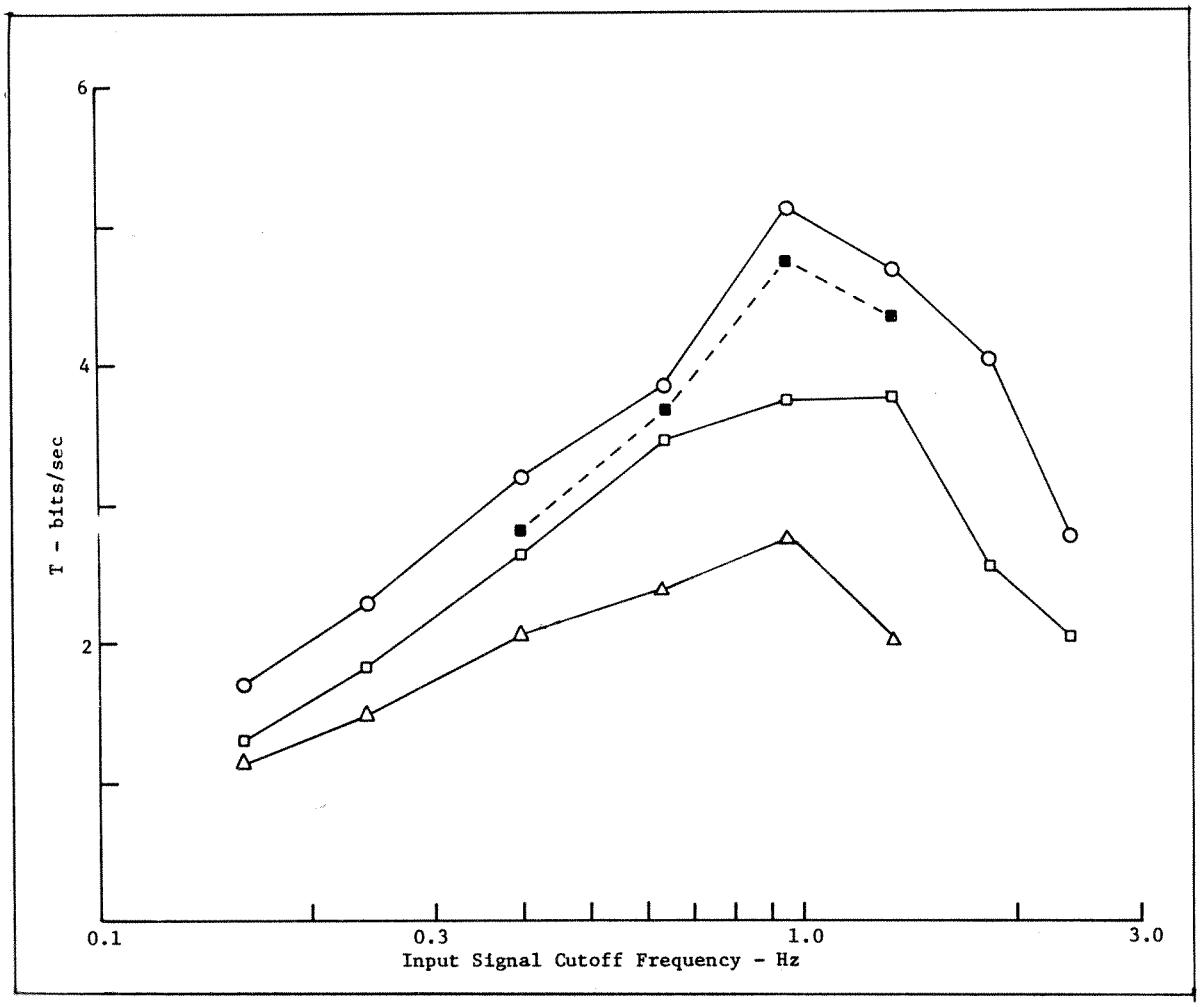

FIGURE 7
Comparison of the information transmission rates for one-dimensional tracking tasks performed by the same subject with the physiological wrist and with shoulder-effected position and velocity control using shoulder protraction-retraction.

○ Physiological wrist
□ Shoulder-effected position control (initial gain)
■ Shoulder-effected position control (increased gain)
△ Shoulder-effected velocity control

quency. All the data in these figures were obtained from the same subject. To allow direct comparison, the data for control using shoulder elevation-depression are plotted with data for tracking with the physiological elbow, the prosthesis function proposed to be controlled. Similarly, the data for tracking controlled with shoulder protraction-retraction are plotted with data for tracking with the physiological wrist. In Figure 8, the total information transmission rates for the two-dimensional tracking tasks, obtained by summing the rates for the individual channels, have been plotted.

These results clearly show that, when the shoulder is used as the control input, position control is significantly superior to velocity control in terms of information transmission capabilities in tracking tasks. For one-dimensional tasks, depending on the position control mapping relationship, the maximum information transmission rates achieved with position control were from 1.0 to 2.6 bits/sec higher than those measured for precisely the same tasks performed using velocity control. This difference corresponds to a 36 percent to 107 percent increase in the information transmission rates between velocity and position control. For the two-dimensional tasks, the maximum total information transmitted over both channels was from 1.8 to 3.8 bits/sec higher with position control than with velocity control, representing a 41 percent to 86 percent increase.

The data in Figures 6–8 also indicate that, with the proper selection of control mapping relationships, shoulder-effected position control of a highly responsive prosthesis mechanism could yield tracking performance comparable to that realized with physiological control of the natural elbow and wrist. As can be seen, tracking performance for shoulder-effected position control was considerably better for the increased-gain control mapping relationship in which 1/2 of the full range of shoulder motion was mapped into the full range of tracking follower excursion—as compared to that for the initial control mapping relationship in which the full range of shoulder motion was mapped into the full range of follower excursion. The poorer performance with the initial mapping relationship was probably due to dynamic control limitations associated with producing large-excursion shoulder movements.

All the data presented in Figures 6–8 were obtained from a single subject. Comparable data were obtained for shoulder-effected position- and velocity-controlled tracking by the other subject who performed those experiments.

Discussion and Conclusions

In respect to the fundamental objectives of this investigation cited in the previous section, it appears that (i) an EPP controlled prosthesis in which wrist rotation and elbow flexion are controlled by shoulder protraction-retraction and elevation-depression could exhibit functional characteristics comparable to those of the physiological elbow and wrist, as defined by tracking capabilities, and (ii) shoulder-effected position control of prosthesis function has considerably more potential for providing effective control than similarly effected velocity control. Both of these statements are made assuming a prosthesis mechanism with non-limiting dynamic characteristics.

These results indicate the importance of the position control mapping relationship to hypothetical prosthesis performance. It appeared that improved dynamic control of a prosthesis could be obtained by using less than the full range of shoulder motion. It may also be desirable to use less than the full range of shoulder motion in a prosthesis for comfort and cosmetic reasons. Inherent in the concept of EPP control, however, is the idea of being able to sense output position from the proprioceptive sensations associated with the physiological control input. Intuitively, it seems that to relate output position to input position as accurately as possible, it would be desirable to map output position into as much of the full range of input control motion as possible. This performance tradeoff would have to be considered in an actual design.

The difficulty of effectively controlling multifunctional prostheses with velocity control is a significant problem in prosthesis design. One of the reasons for performing the two-dimensional tasks in this investigation was to examine and compare multifunctional velocity control with multifunctional position control. It was initially hypothesized that the relative effectiveness of position control would be even more obvious for two-dimensional control than for one-dimensional control. This expectation was derived from the concept that position control is more natural and able to be effected at a more subconscious level of attention than velocity control. It seemed likely that this effect would manifest itself in terms of the relative degradation in tracking performance observed for the individual functions when comparing solo performance in one-dimensional tasks with simultaneous performance in the two-dimensional tasks.

It was somewhat surprising, therefore, to see that the data for these experiments indicate that the relative degradation in performance between tasks performed individually and simultaneously

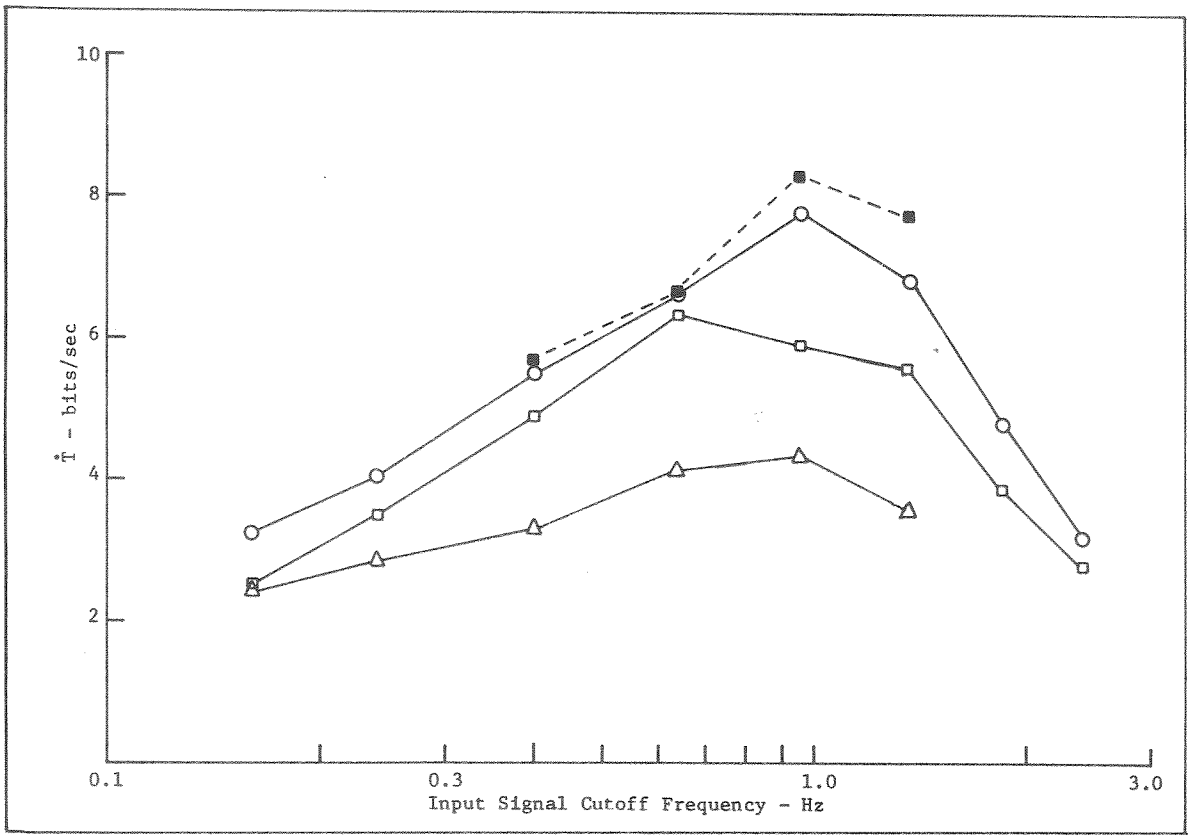

FIGURE 8
Comparison of the total information transmission rates for two-dimensional tasks performed by the same subject with the physiological elbow and wrist and shoulder-effected position and velocity control. These data were derived by summing the rates for the individual channels in the two-dimensional tasks.
○ Physiological elbow and wrist
□ Shoulder-effected position control (initial gain)
■ Shoulder-effected position control (increased gain)
△ Shoulder-effected velocity control

was no greater for velocity control than for position control. In these experiments, however, the subjects were expected to concentrate solely on the experimental tasks. Thus there was no attempt or means to determine the level of possible subconscious involvement. Other than the fact that velocity control is inherently more difficult, these results do not indicate any fundamental differences between the psychological mechanisms associated with effecting velocity control and position control while directly attending to task performance, although it is still hypothesized that differences do exist.

SUMMARY

This research was devoted to an investigation of the effectiveness of applying the concept of extended physiological proprioception to the control of upper-extremity prostheses. It was originally hypothesized that EPP control derived from residual shoulder motion could be advantageously applied in multifunctional prostheses for shoulder disarticulation amputees.

This paper described a study of the ability of subjects to control physiological shoulder elevation-depression and protraction-retraction as prosthesis control inputs. For the study, extensive experiments were conducted analyzing the ability of subjects to perform one-dimensional and two-dimensional pursuit tracking tasks for continuous random input signals. The tracking experiments were performed using shoulder-effected position and velocity control of function. For comparison purposes. equivalent experiments were also per-

formed for tracking with physiological elbow flexion-extension and wrist rotation, the physiological functions to be controlled in the proposed prosthesis. Tracking performance was specified in terms of response information transmission capacity, based on the premise that the effectiveness of prosthesis control is in large part determined by the ability of the user to communicate his motor intent to the prosthesis.

The results of this study showed that, for a hypothetical prosthesis mechanism with non-limiting dynamic response characteristics, an EPP-controlled prosthesis in which wrist rotation and elbow flexion are controlled by shoulder elevation-depression and protraction-retraction could exhibit functional characteristics comparable to those of the physiological elbow and wrist, as defined by tracking capabilities. The results of this study also indicated that shoulder-effected position control of prosthesis function has considerably more potential for providing effective control than similarly effected velocity control.

Motivated by the findings of the study just described, an experimental prosthesis was built for further evaluation of the concept and principles of EPP control. The design and evaluation of the experimental prosthesis are detailed in a companion paper (13) ■[b]

[b] The companion paper follows on page 19.

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