MANIPULATORS

A MULTI-MODE APPROACH TO COORDINATED PROSTHESIS CONTROL

L.E. Carlson and C.W. Radcliffe

Summary

External power has the potential for improving the dynamic function of arm prostheses, since several units can be made active. However, simultaneous, coordinated control of several degrees of freedom is generally not feasible because the mental decision load on the amputee becomes excessive. Clearly, some form of control hierarchy that relieves the amputee of part of the control responsibility would increase a device's versatility.

The multi-mode concept utilizes kinematic coupling to coordinate several joint motions in fixed patterns. The provision of a few distinct patterns, or models, allows the amputee to create a wide variety of useful motions by consecutive operation of different modes. Prosthesis operation is a two-step process! mode selection followed by actuation. If the phases are kept simple and independent, the amputee's decision load is minimized.

To test the multi-mode concept, a pneumatically-powered above-elbow prosthesis was built with three degrees of freedom: elbow flexion, wrist flexion and wrist rotation. A digital logic circuit interprets selection pulses from two body-actuated microswitches to set and hold the desired mode. Humeral flexion then generates the appropriated motion by operating two miniature pressure demand valves with closed-loop position control.

The results of amputee testing were positive. Each phase of the two-step operation process was quickly mastered, and combining the two phases was no problem. The amputee learned to move the arm quickly and smoothly through near-optimal trajectories, and regarded the increased versatility provided by the additional degrees of freedom as a strong asset.

Concept

One of the goals of upper-extremity prosthesis design is to provide natural motion patterns coordinating several joints, for example elbow and wrist. Simultaneous control of independent actuators increases the amputee's mental decision load, however, seriously limiting the benefits of multi-joint control. Many methods have been explored to reduce the decision load and thereby improve coordinated control, including pattern recognitation /1/, coordinate control /2, 3/, playback of recorded motion patterns /4/, and multi-level control systems /5, 6/. The oldest approach is kinematic coupling, dating back to Charriere in 1860 /7/.

Kinematially-coupled prostheses, while providing coordinated motions, have had certain drawbacks. They were usually too limited, with one coupled elbow wrist motion and one elbow-only motion. Selection of the mode often required the other hand, and independent wrist motion was generally not possible. In any given mode of operation, however, kinematic coupling is a simple, practical means of acheving coordinated multi-joint control.

The concept embodied in the multi-mode approach is to retain the advantages of kinematic coupling while eliminating or reducing the disadvantages. This is accomplished by providing several useful patterns and a simple method to select the desired pattern.

The Berkely Multi-Mode Arm /8/ is an above-elbow prosthesis with three degrees of freedom: elbow flexion, wrist flexion and wrist rotation. It is capable of four distinct modes of operation. The parallel mode (Fig. 1) keeps the terminal device parallel to its initial position at all times, the same pattern provided by Simpson's parallelogram feeder arm /9/. It enables an amputee to raise a glass without spilling its contents, for example.

The coupled mode (Fig. 2) couples wrist rotation and flexion to elbow flexion as follows:

Elbow flexion	Supination	Wrist flexion
120°	95°	25°

Similar to the patterns of the Carnes (1912) /10/ and Northrop (1951) /11/ arms, this mode provides a very natural motion useful in eating and many other activities. The two remaining modes provide independent wrist motions with a locked elbow, useful for terminal device (TD) repositioning. The wrist can flex 180° in the wrist flexion mode (Fig. 3). In addition to its value for repositioning, it enables the amputee to flex the TD out of the plane of elbow flexion closer to his body. The rotation mode (Fig. 4) provides 130° of active pro/supination, useful for eating as well as many rotational activities, e.g. turning a doorknob. As in the coupled mode, a slight amount of wrist flexion accom-

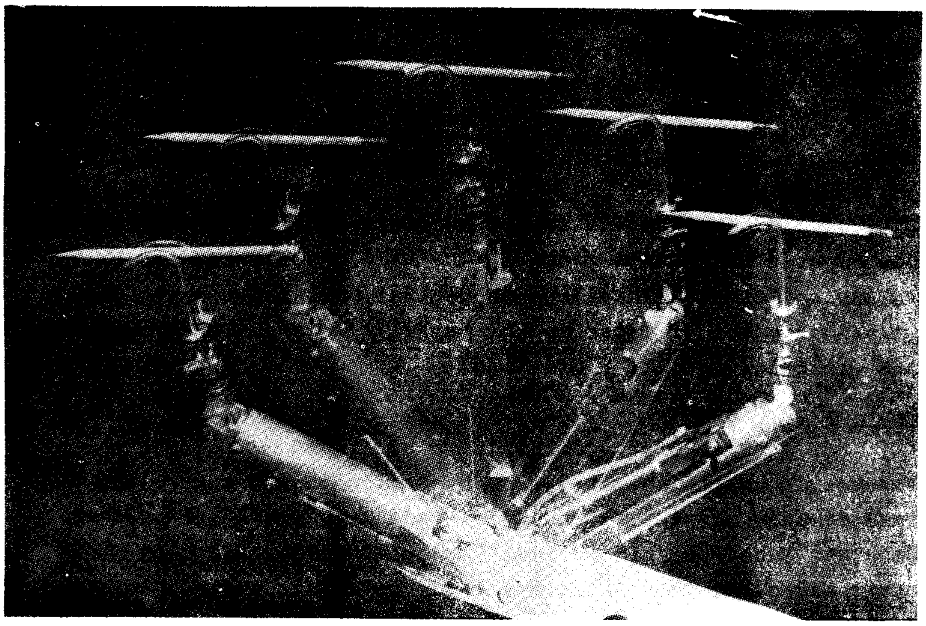

Fig. 1. Mode 1 - Terminal device parallel

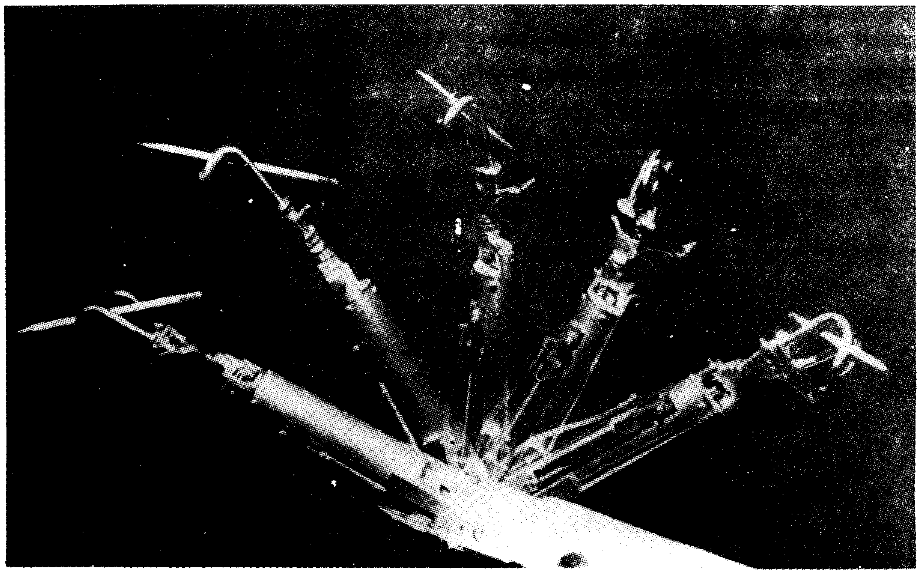

Fig. 2. Mode 2 - Rotation coupling

panies supination in the ratio of 1:3.8. This brings the TD closer to the body as it supinates, providing a more natural motion.

Prosthesis operation is a two-step process. The amputee first selects the desired mode with digital signals, and then actuates the motion with proportional position control. Kinematic coupling in any given mode allows him to control up three degrees of freedom as one.

Since selection and actuation are completely independent the amputee can change modes at any time or with the prosthesis in any position. This allows sequential motion patterns, such as raising a glass of water in the parallel mode and then pronating the wrist to tip it for drinking.

Control

For a multi-mode prosthesis to be of maximum use to the amputee, both the selection and actuation phases must place minimal demands on him. In the Multi-Mode Arm, gears are used to generate the four kinematically coupled modes, and both pneumatic and electronic logic are used to select and maintain the desired mode. As seen in Figure 5, four pneumatic cylinders are involved in prosthesis operation - two power cylinders and two miniature control cylinders. The elbow power cylinder moves the prosthesis in modes 1 and 2, while the wrist power cylinder,located adjacent to it, drives the wrist-only modes. Miniature spool valves located in the forearm switch the flow of gas appropriately (Fig. 6).

The control cylinders can be thought of as binary actuators having two possible states: on (pressurized) or off (unpressurized). The four modes represent the possible combinations of the two actuators. For modes 1 and 2, the coupling cylinder is off, fixing the elbow shaft and leaving the elbow free. If the wrist selector cylinder is also off, the wrist gears are desengaged and wrist rotation is locked out. Elbow flexion then causes the wrist drive shaft to flex the wrist, keeping the TD parallel (mode 1). If, on the other hand, the wrist selector cylinder is pressurized, the wrist gears will be engaged and will cause the wrist to supinate and flex slightly in concert with elbow flexion (mode 2). Actuating the coupling cylinder locks the elbow and releases the elbow shaft so that it can be driven by the wrist cylinder determines the effector of drive shaft rotation on the wrist. If it is off, the system is in mode 3; if on, mode 4.

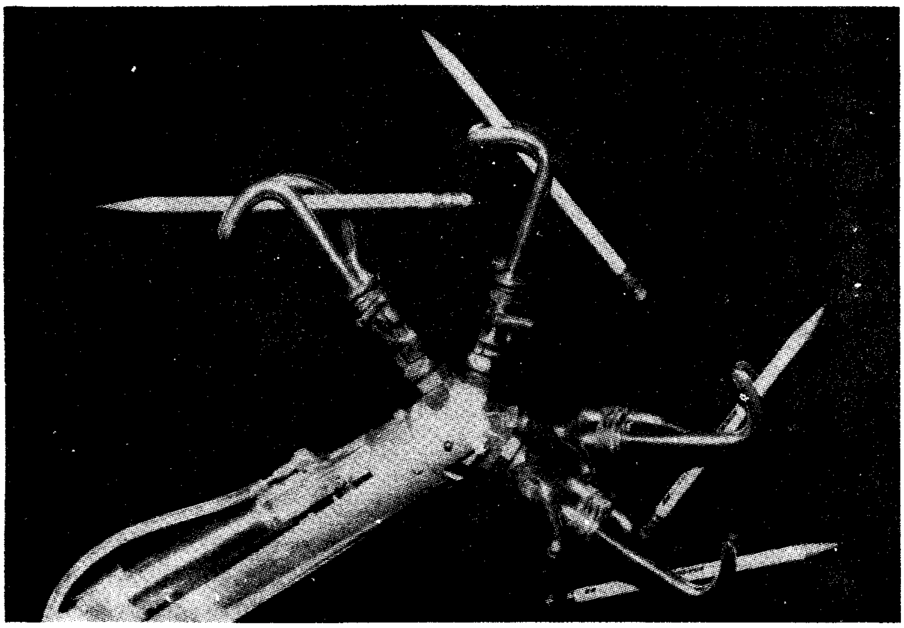

Fig. 3. Mode 3 - Independent wrist flexion

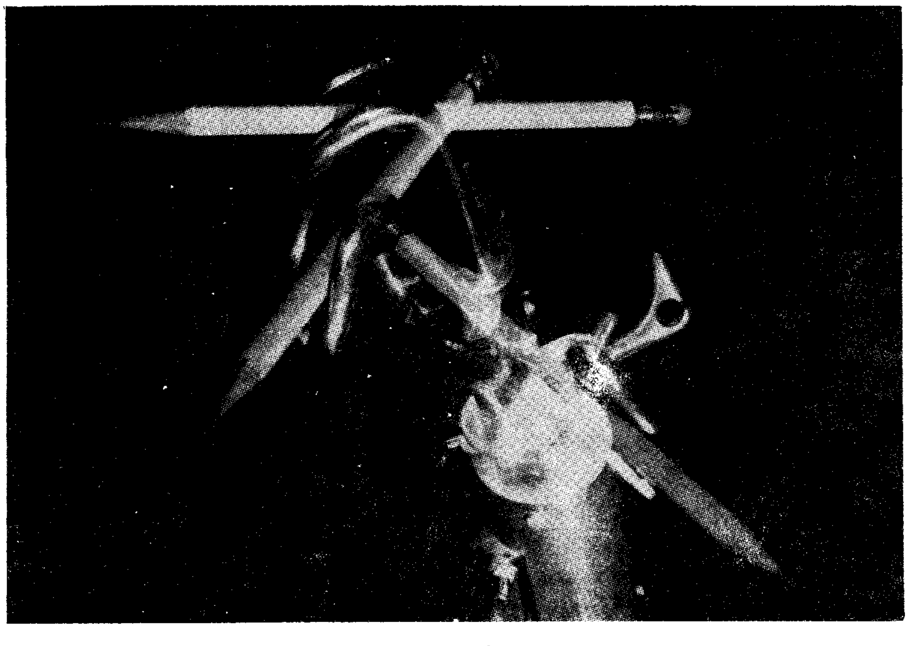

Fig. 4. Mode 4 - Independent wrist rotation

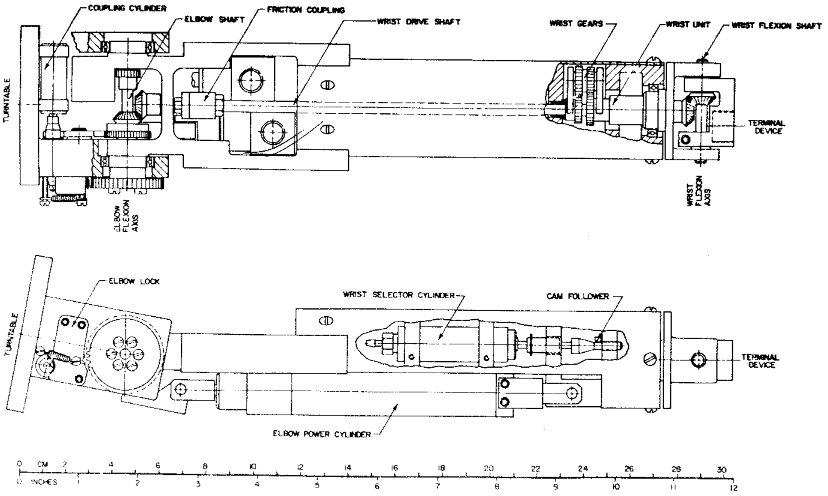

Fig. 5. Multi-Mode Arm
- assembly drawing

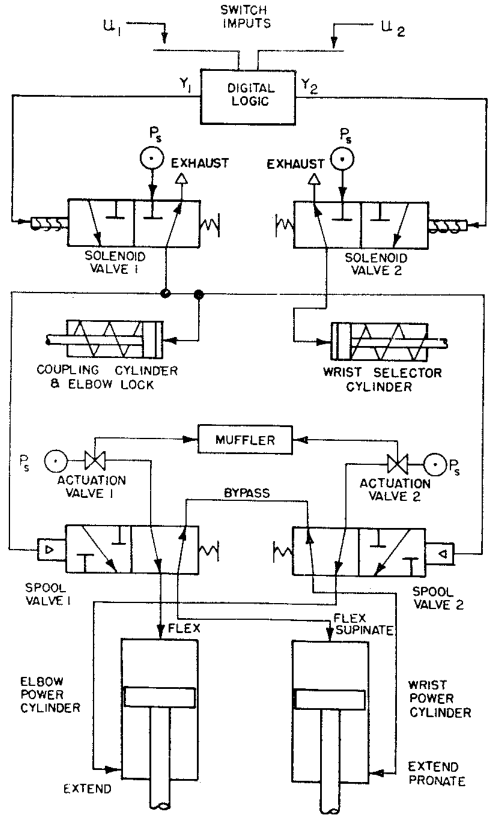

Fig. 6. Control circuitry

To take advantage of the versatility of electronic logic, solenoid valves are used to actuate the pneumatic control cylinders. For this prototype, no attempt was made to optimize the solenoids, which consume excessive power in their "on" states. A more practical system with very low power drain could easily be built, however, using miniature solenoid valves such as those developed in Sweden /12/. Since these valves allow separate control over inlet and exhaust, power need only be consumed when switching modes.

To minimize the amputee's decision load in mode selection, digital intergrated circuit logic provides an interface between the solenoids and the amputee, who pulses two microswitches with relative motions. The requirements of the mode selection logic--circuit are:

1) It must require inputs only to change a mode, not maintain it; i.e. it must be temporally independent of actuation.
2) It must allow random access, so the system can go directly from any mode to any other desired mode.
3) It must not require knowledge of the present mode to switch to the desired mode.
4) It must require only one step.

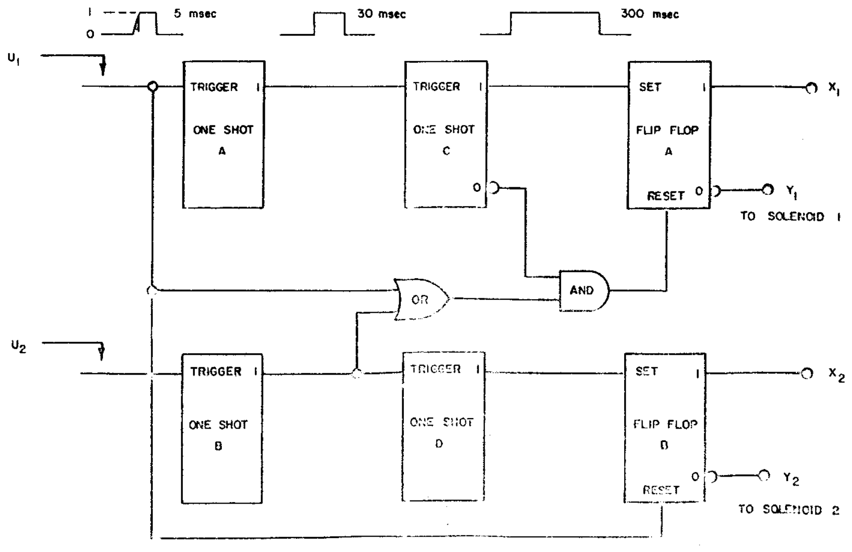

Fig. 7. Mode selection logic circuit

The logic circuit of Figure 7 meets these objectives. The flip-flop elements serve as the memory of the system and the one--shots are monostable multivibrators which provide pulses of timed duration. One-shots A and B simply eliminate any effects of contact bounce in the switch inputs U_1 and U_2, while one-shots C and D generate adjustable timing pulses, typically of 300 msec. This allows inputs within 300 msec of each other to be interpreted as simultanous.

The resulting pulse code is listed in Table 1. For example, the amputee selects mode 2 by pulsing switch U_1 only, while pulsing both switches simultaneously selects mode 1. Mode 4 is triggered by holding switch U_1 longer than 300 msec.

Table 1. Mode Selection Pulse Coding

Mode	Input Pulse		Output State	
	U_1	U_2	Y_1	Y_2
1	1	1	0	0
2	1	0	0	1
3	0	1	1	0
4	1*	0 or 1	1	1

* a pulse longer than 300 msec

The switches were mounted bilaterally on the harness chest strap and on the medial wall of the socket, so that humeral adduction against the torso would activate the switches (Fig. 8). This proved to be reliable and reasonably free from inadverent operation. It also had the advantage of being integral with the control harness and socket, simplifying donning and adjusting the system.

Once the amputee has selected the mode, he then uses glenohumeral flexion to move the prosthesis with position control, similar in principle tp the Navy-Fitch body-powered arm /13/. This control action is harnessed by suspending the socket from two ends of a Bowden cable which loops around a pulley at the elbow. Glenohumeral motion therefore lengthens one end of the cable and shortens the other, rotating the pulley. Two NBI pressure-demand valves /14/, whose output is proportional to applied force, are mounted back-to-back on the forearm and actuated by a control yoke attached to the pulley (Fig. 9).

This valve arrangement results in closed-loop elbow position control in which the forearm maintains the set point signalled by glenohumeral flexion via the pulley. Elbow position is therefore proportional to glenohumeral angle. This relationship remains constant with varying load and arm orientation, providing a proprioceptive feedback path. In addition, the linearity of the valves makes the system force reflecting; i.e. the required cable force is dependent on the load being lifted. Other advantages of this closed-loop control are markedly increased stiffnes and the fact that a sudden change in load, due to a heavy load being dropped, for example, will not cause the arm to rapidly fly up. Instead, the elbow will return to its initial equilibrium position.

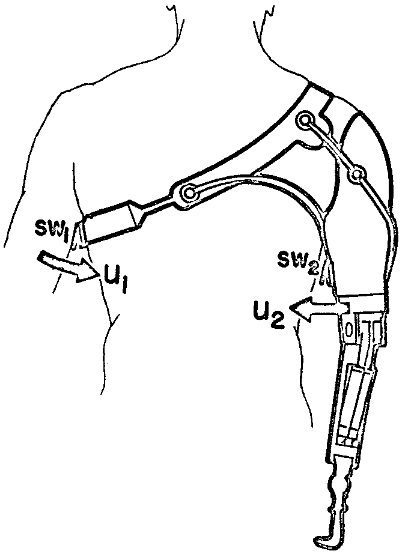

Fig. 8. Mode selection control sites

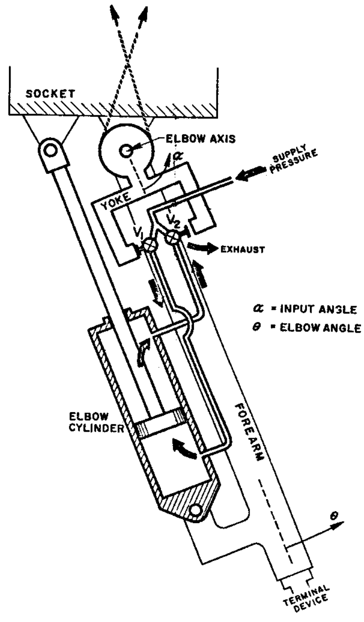

Fig. 9. Closed-loop position control

Performance

The Multi-Mode Arm was fully instrumented and fitted to a right above-elbow amputee for laboratory trials (Fig. 10). Potentiometric position data were digitized, recorded on IBM-compatible tape and processed by a CDC 6400 for quantitative evaluation to augment qualitative evaluations of the amputee and tester.

For purposes of discussion, the results can be separated into two aspects: performance of the elbow only, which can be compared with other powered elbows, and performance of the entire multi-mode system. This distinction is important since the prosthesis, when considered as an elbow, must be at least as good as other elbows before the multi-mode approach can offer any significant advantages to an amputee.

Fig. 10. Laboratory trials with the instrumented prosthesis

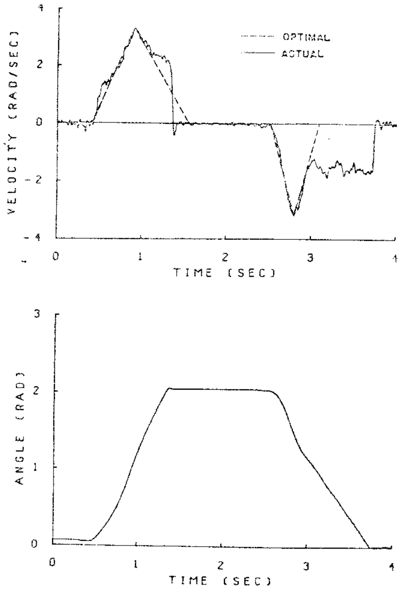

Fig. 11. Position and velocity vs. Time - elbow motion

Comparation of the Multi-Mode Arm with nine externally-powered elbows from the United States /15/, Canada /16/ and Sweden /12/ shows it to be competitive. It delivers 6.3 Nt-m elbow torque and has a minimum no-load flexion time of 0.8 seconds. With a 455 gm. load, flexion time is 1.5 seconds. Since control is proportional, the amputee can also move the elbow as slowly as desired. At all speeds, the prosthesis is very quiet, less than 40 db.*

A plot of elbow velocity versus time (Fig. 11) shows that the motion approaches a triangular wave form characteristic of

*Highest value measured on A, B, C and linear scales, 1 meter from sound source.

time-optimal control found in normal arm movements /17/. The deviations are due mainly to the viscous damping of the exhausting gas. This effect is more pronounced during extension since more gas must be exhuasted.

Control of the wrist in modes 3 and 4 was also smooth, although not as precise as elbow control. With no load, the control action was effectively velocity controlled, which tended to drift somewhat.

The mode selection phase was learned quickly, and was relatively free from inadvertent operation. The modes most reliably selected were those requiring only one short pulse, and these pulse codes can be assigned to the two modes most frequently used by the individual amputee, minimizing his decision load.

The amputee's reactions to the prosthesis were positive. He found the system easy to learn and operate, and felt that both the kinematic coupling of wrist and elbow motions and the capability of independent wrist motion offered significant improvements over his conventional prosthesis. Since the mode selection and actuation phases are independent, he also became proficient at sequential operations such as flexing the elbow to elevate the TD and then flexing the wrist to get close to his body.

Conclusions

The multi-mode approach to coordinated prosthesis control provides several kinematically-coupled motion patterns and a method to select the desired mode simply and reliably. Since the selection and actuation phases are independent, the amputee's decision load is minimized and the versatility of the prosthesis is improved. Amputee tests of the Multi-Mode Arm suggest that this approach is a feasible method of generating coordinated prosthesis motion patterns.

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