ARM PROSTHESES AND ORTHOSES

KINESTHETIC SENSING FOR THE EMG CONTROLLED "BOSTON ARM"

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The contribution of a novel, cutaneous display of elbow angle to an amputee's ability to position an EMG controlled, externally powered elbow prosthesis was objectively evaluated. Comparisons were made between the amputee's positional control of his conventional mechanical, cable-operated elbow and the EMG "Boston Arm" elbow, with and without angle feedback, in REACHING tasks with vision occluded in all cases and with and without auditory occlusion. MATCHING tasks compared his ability to position the EMG limb to conform with the flexion of his normal (contralateral) elbow. Computer reduction of almost 9,000 individual trials and analysis of variance indicated that for the EMG limb the tactile feedback with sound occluded reduced errors by fifty percent. Terminal device load did not significantly affect positioning performance due to the force proprioception built into the "Boston Arm." In comparison with the standard mechanical prosthesis the EMG limb with feedback achieves virtually identical kinesthetic performance. The display is completely compatible with the EMG control, causes no discomfort to the wearer and is not significantly degraded by the environmental conditions of the limb socket.

Research Goals

The normal intact human in the absence of vision relies upon the kinesthetic senses to establish the absolute angle across anatomical joints. An above-elbow amputee fitted with a conventional, cable-operated, mechanical elbow prostheses learns to associate the extent of shoulder-rounding (which through the harness pulls the cable) with the resulting angle which the forearm portion of the prostheses makes with the upper arm socket and stump. The proprioception of torque across the joint due to terminal device load is also inherent in cable prostheses.

Prostheses deriving control information from bioelectric sources in the body eliminate the need for gross body movements and direct use of body power of cable prostheses. When coupled cybernetically to the human central and peripheral nervous systems, as

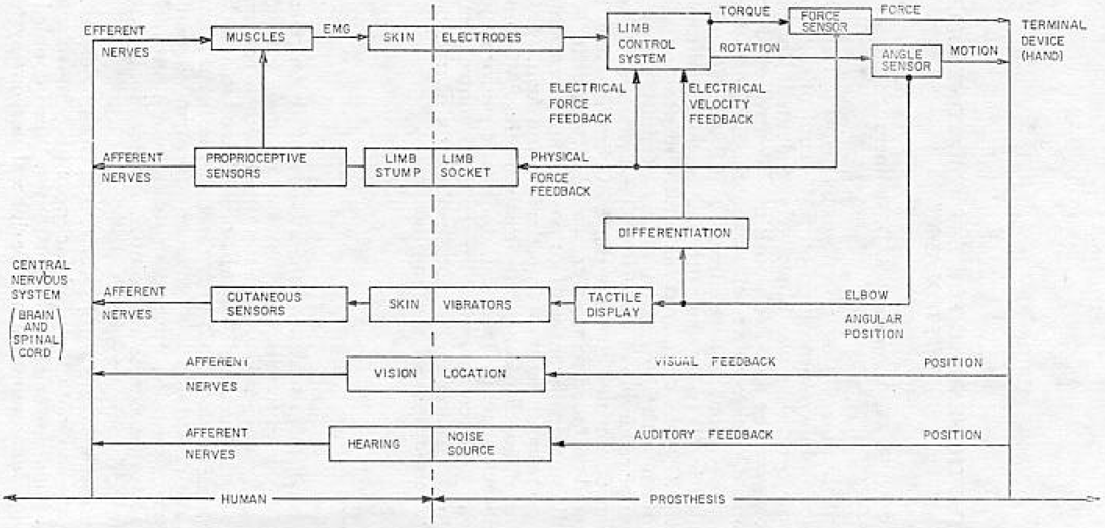

Fig. 1. A block diagram of "Boston Arm" showing efferent muscular control and afferent sensory interface between human and prosthesis.

when electro-myographic signals (EMG) from muscle which previously controlled the joint that was amputated are utilized, training is virtually eliminated and amputees achieve volitional efferent control immediately after fitting. Proprioceptive force sensing has been achieved in the EMG limb known as the "Boston Arm" [1] by electronically sensing force and feeding this information back to the limb servo-mechanism in opposition to the body-generated EMG signal. The resulting demand for additional muscular output from the subject stimulates force sensing organs in the residual muscles and at the interface between the limb socket and stump, see Figure 1.

Even so, an EMG limb does not provide the afferent nervous system with a direct measure of joint angle as does the cable. Our research is concerned with comparing the absolute angle positioning ability of a unilateral above-elbow amputee using an EMG controlled limb with and without a novel cutaneous display of elbow angle versus his cable-operated prostheses and his normal (opposite) limb [2].

The incorporation of kinesthetic sensing into the EMG controlled limb also raises questions of compatibility and interaction since the human's efferent senses for control and the human's afferent senses for feedback must respond simultaneously.

Finally we wished to employ quantifiable, psychophysical measurement techniques in the limb control comparison rather than relying on anecdotal and qualitative expressions of opinion so common in prostheses evaluation.

Apparatus and Procedure

The experimental apparatus designed to evaluate the amputee's performance with prostheses in the REACHING task consists of a vertical panel, (Fig. 2) on the front side of which, in the visual field of the subject, ten targets with lamps on their ends are arranged on 4.5 inch vertical and horizontal spacing as in Figure 3. The locations of the targets (on the rear panel surface) are all accessible to the subject thru flexion of his elbow or other limb motion but are not visible to him, (Fig. 4). Upon illumination of one of the target lamps, the amputee flexes his elbow and attempts to touch the corresponding point on the rear of the panel. Contact extinguishes the lamp and records on a Hollerith card the time to, and the horizontal and vertical coordinates of, contact, plus other identifying data such as the test condition, target position, etc. After a three second delay another lamp is automatically illuminated by the test console.

Two sequential procedures were adopted for the REACHING task. In one, the standard-start, the amputee was instructed to return to the normal rest (fully extended) position between target identifications. The target position order was random. In the second procedure, point-to-point, the amputee was instructed to move directly to the next illuminated position. The presentation patterns were designed to emphasize horizontal or vertical motion, pure elbow rotation, or were random in order.

Fig. 2. Subject reaching for one of the targets on front of panel.

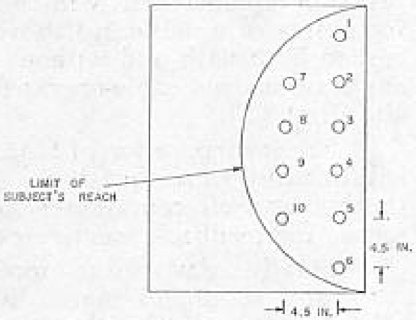

Fig. 3. Target Panel showing target locations and limits of the subject's reach.

For each procedure the subject was tested with no load or with loads on the terminal device ranging from zero to 700 grams. This series was intended to explore the contribution of the force proprioceptive feedback of the prostheses, since at increased terminal device loads proprioception should be enhanced.

Each testing series consisted of 200 reaching trials consisting of five groups of 20 trials, each performed twice, once with position feedback off and once with feedback on. Within each group each target was presented twice with a different order of presentation for each of the five groups. During the load test the weights were changed every ten trials. Figure 5 gives a typical order of performance of trials.

Since it became apparent that the amputee was using auditory cues for positioning (the limb used was an early model and relatively noisy) all tests with the EMG limb were repeated with and without sount occlusion.

The data cards automatically recorded by the test console, representing 8,800 separate test points, were processed by digital computer to yield averaged and comparative results and were also subjected to analysis of variances evaluation. The raw data is published in [2] along wtih other aspects of the investigation which cannot be reported here due to space limitations.

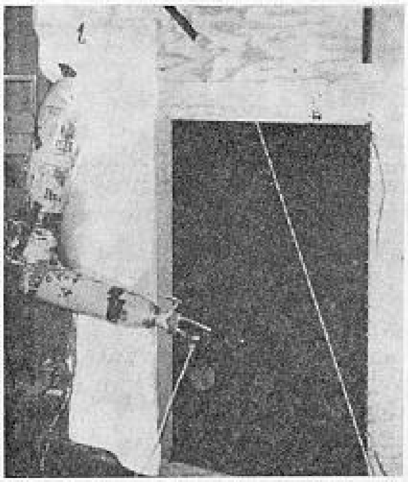

Fig. 4. Rear view of panel showing subject's prosthesis and X—Y coordinate measuring system.

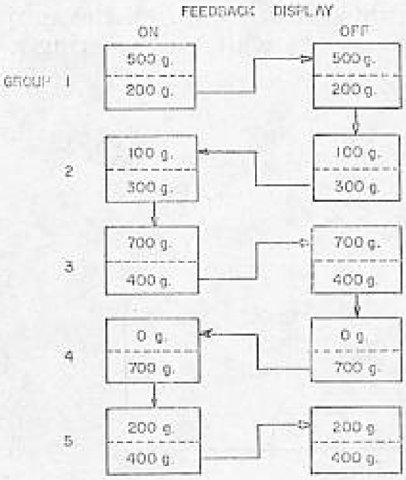

Fig. 5. Order of performance of trials in the REACHING tasks. Each block represents 20 trials, 2 for each target pin. Application sequence of weights in the loaded REACHING tasks.

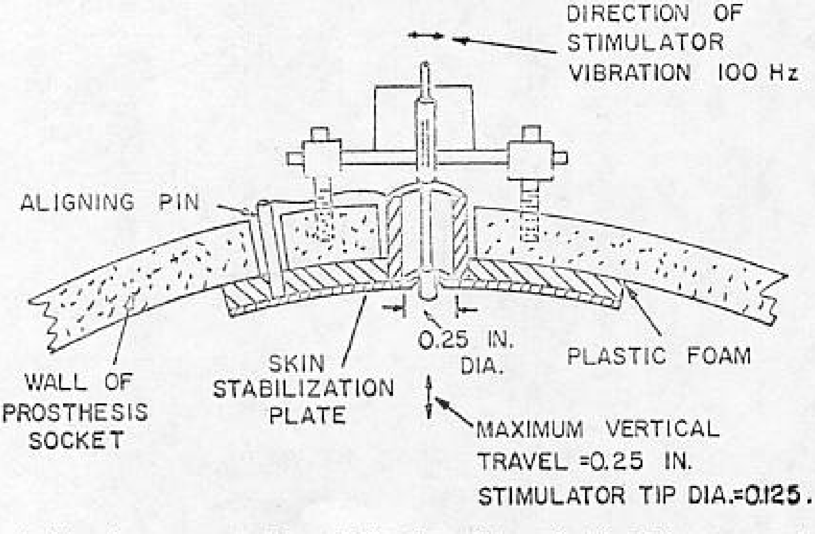

Fig. 6. Stimulator mount, skin stabilization plate and stimulation parameters.

A different task, the elbow angle MATCHING task was designed primarily as a control on the REACHING task. MATCHING measured the ability of the amputee to bring the prostheses to the same position as that of his normal limb. As an additional control, a third task measured the subjects ability to READ the display on his stump while not wearing a prosthesis.

Prostheses

The mechanical prosthesis was the standard shoulder harness, cable-operated free-or-locked elbow joint unit.

The EMG operated prosthesis was the so-called "Boston Arm", EMG potentials are recorded by skin electrodes over the residual bicep-tricep muscles. In this particular case the amputee had a relatively short stump. The EMG signals control an electro-mechanical servo-

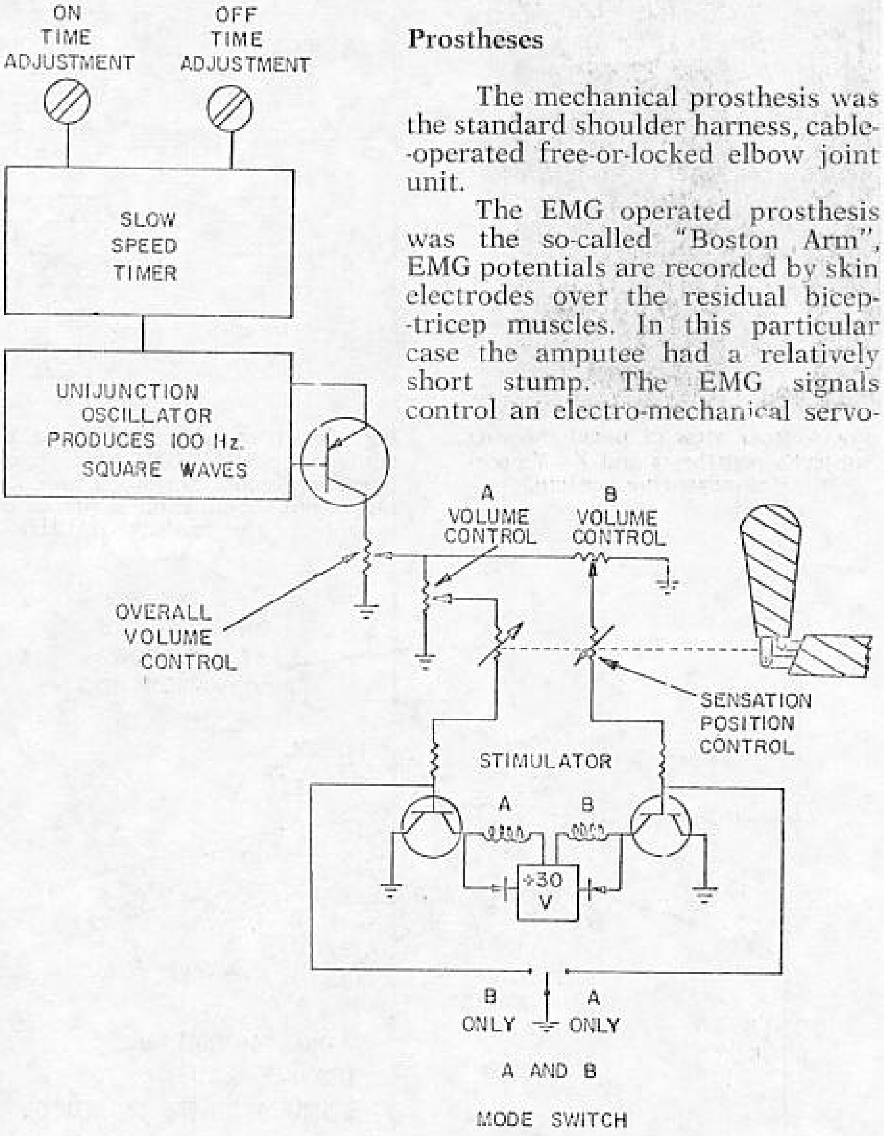

Fig. 7. Overall schematic of phantom sensation circuit.

-driven elbow joint, and are opposed by a force feedback signal detected by a sensor in the prostheses. In normal operation of the limb the amputee employs vision as one form of afferent feedback. This route was occluded in all tests reported on here. We found that auditory feedback can provide suprisingly accurate position feedback cues.

For the tactual display of limb angle a technique researched by Alles [3] based on the phantom position phenomenon of Von Bekesy was installed in the upper arm socket of the limb. Figure 10 is a cross-sectional view of the upper-arm socket showing the mounting of one of the vibrotactile stimulators, the skin stabilization plate and the stimulation parameters.

Two of the electro-mechanical stimulators are mounted four inches apart in contact with the amputees' stump and stroke the skin tangentially with pulses of 100 Hz. vibration as indicated by the overall schematic of Figure 7. The amplitudes of the respective stimulators are related to elbow angle according to

$$\text{amplitude of } A = A \log [1.6 (1-p) + 1.14]$$

$$\text{amplitude of } B = B \log (1.6 p + 1.14)$$

where p is normalized angular position between extremes of flexure. This logarithmic inverse relationship of respective amplitude gene-

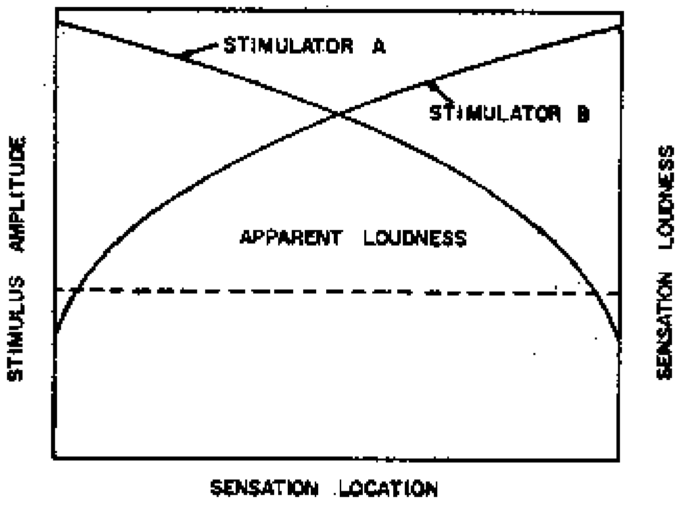

Fig. 8. Logarithmic variation of stimulator amplitudes.

rates a perceived stimulation of constant apparent loudness on the skin whose location between the fixed stimulators corresponds to the elbow angle, (Fig. 8).

Research Results

For the REACHING tasks the horizontal X and vertical Y errors were combined for each target location to give the average radial error R, a measure of accuracy. Then the average radial error of each test point about the average response position was calculated RR, giving a measure of precision or the subjects ability to reproduce a given position, (Fig. 9). RR is considered the more useful of the two measures since it is not influenced by any shifts in the subjects hand-to-eye coordination.

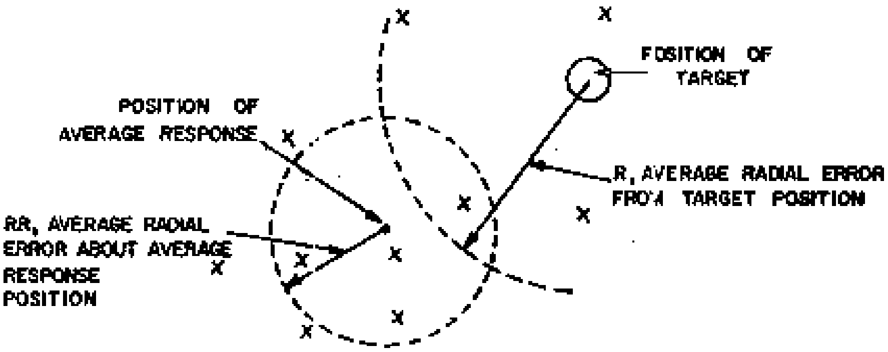

Fig. 9. Measures of positioning performance for the REACHING task.

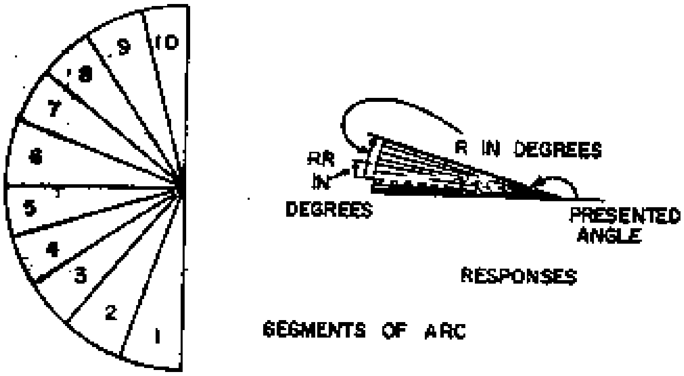

Fig. 10. Elbow flexion segments and positioning parameters for MATCHING task.

For the MATCHING task the elbow flexon arc was divided into ten equal segments with metrics R and RR similar to the REACHING task, (Fig. 10).

Figure 11 gives the variation of R and RR for the MATCHING task using the EMG limb with the tactile feedback off and on. Note the dramatic reductions in both R and RR, but specially RR where the improvement due to the feedback is a factor of three.

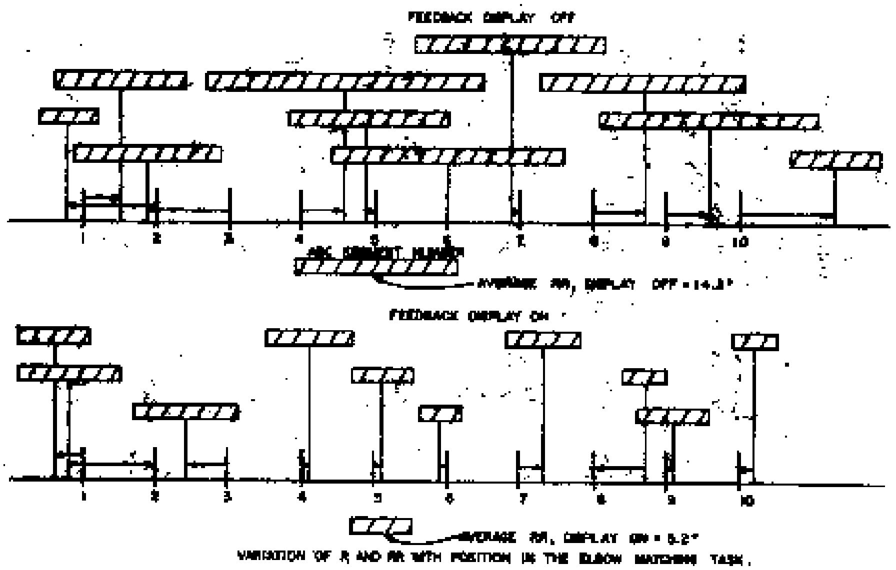

Fig. 11. Accuracy and precision of the EMG limb with and without tactile feed back for the elbow MATCHING task.

Table 1 reports the results of the REACHING test and their analysis of variance. The correlation of R and RR was checked using the Pearson Correlation Coefficient r. The high correlations for the EMG limb indicate that the response points were almost evenly distributed about the target.

The data indicates that the Alles' display significantly improves the amputee's performance with the EMG limb. Load has little influence. Sound cues contribute significantly to accuracy, particularly for the standard start, but not as much to precision. There was generally no statistical interaction between target position and display condition (V×P).

Table 2 compares data and analyses of variances for the EMG vs. mechanical prostheses. The poor correlation of R and RR for the mechanical limb (Not Significant level of r) indicates the general tendency of the subject to be too low (large negative values of Y) with this displacement increasing with target height, the familiar limitation of cable prostheses at acute elbow flexions.

Direct comparison of EMG and mechanical performance shows that for the sound occluded condition the subjects' average

TABLE I
Results of the REACHING Tests and the Analysis of Variance

CONDITION		X	Y	R	RR	Significance level of r		Analysis of Variance significance level of: Main effects R	Main effects RR	interactions R	interactions RR
Standard Start Sound Occluded	Display on, load on	—7	—1	16	12	.001	D	.001	.001		
	" on, " off	0	—4	19	17	.001	L	.005	.01	none	none
	" off, " on	—1	—1	28	27	.001	P	.001	.04		
	" off, " off	5	14	38	32	.001					
Point to Point Sound Occluded	Display on, load on	—6	—5	20	17	.001	D	.001	.001		
	" on, " off	—5	—7	15	11	.01	L	NS	NS	none	
	" off, " on	—8	1	35	32	.001	P	.001	.01		none
	" off, " off	—2	—16	38	32	.008					
Standard Start Sound Unoccluded	Display on, load on	—7	—5	18	13	.001	D	NS	.025		
	" on, " off	5	—9	21	17	.001	L	NS	NS	none	VxP .01
	" off, " on	—7	—5	22	18	.001	P	.001	.01		
	" off, " off	7	—9	24	19	.001					
Point to Point Sound Unoccluded	Display on, load on	—8	—5	23	17	.001	D	.001	.001	VxP, .001	VxP, .001
	" on, " off	—1	—10	23	20	.001	L	NS	NS		LxP,
	" off, " on	—10	—4	35	30	.001	P	.001	.001	LxP, .001	.001
	" off, " off	2	—4	32	29						
Mechanical Prosthesis	P.T.P., load on	3	—22	25	11	.10 : NS					
	P.T.P., load off	7	—14	23	13	NS					
	S.T.D., load off	6	—29	34	15	NS					
Normal Arm	S.T.D., load off	5	—6	11	7	.01					

D—Feedback display
L =Load
P =Position
X—average horizontal error
Y—average vertical error
each unit represents 0.1 inch

TABLE 2
Analysis of Variance
Emg Prosthesis versus Subject's Own Mechanical Prosthesis

Condition, Point to Point		X	Y	R	RR	Significance level of r		Analysis of Variance Significance level of: Main effects R	Main effects RR	Interactions R	Interactions RR
Sound Occluded Display On	Emg arm, load on	—6	—5	20	17	.001	A	.005	NS	AxP .001	AxP .025
	Emg arm, load off	—5	—7	15	11	.01	L	.05	.01	LxP .003	AxL .001
	Mech. arm, load on	3	—22	25	11	NS	P	.001	.001		LxP .025
	Mech. arm, load off	7	—14	23	13	NS					
Sound Occluded Display Off	Emg arm, load on	—8	1	35	32	.001	A	.025	.001		
	Emg arm, load off	—2	—16	38	32	.001	L	NS	NS	none	LxP .05
	Mech. arm, load on	3	—22	25	13	NS	P	.01	.025		
	Mech. arm, load off	7	—14	23	13	NS					
Sound Unoccluded Display On	Emg arm, load on	—8	—5	23	17	.001	A	NS	.001	AxP .01	AxP .05
	Emg arm, load off	—1	—10	23	20	.001	L	NS	.025		LxP .005
	Mech. arm, load on	3	—22	25	11	NS	P	.001	.005	AxLxP .03	
	Mech. arm, load off	7	—14	23	13	NS					
Sound Unoccluded Display Off	Emg arm, load on	—10	—4	35	30	.001	A	.002	.001	AxP .001	AxP .001
	Emg arm, load off	2	—4	32	29	.001	L	NS	NS	LxP .025	LxP .001
	Mech. arm, load on	3	—22	25	11	NS	P	.001	.001	AxLxP .01	AxLxP .05
	Mech. arm, load off	7	—14	23	13	NS					
Standard Start											
Sound Occluded Display On	Emg arm, load on	—7	—1	16	12	.001					
	Emg arm, load off	0	—4	19	17	.001					
Sound Unoccluded Display On	Emg arm, load on	—7	—5	18	13	.001					
	Emg arm, load off	5	—9	21	17	.001					

Key
A = Arm, Emg prosthesis or Mechanical prosthesis
L = Load
P = Position
X = Average horizontal error
Y = average vertical error

each unit represents 0.1 inch
+ directions are up and away from subject

errors using the EMG prostheses with tactile feedback were not significantly different from his errors with the mechanical prostheses (with which of course he has had much more experience). Actually the average accuracy errors with EMG were lower by about 0.6 inch (significance level .005). With sound plus tactile the errors increased slightly to make average accuracy error for EMG just equal to mechanical, and increased precision error for EMG to about 0.1 inch (significance level .001). When the display was turned off, errors with the EMG limb were significantly (1—2 inches) greater under both conditions.

Conclusions

In positioning tasks carried out under a wide range of conditions the Alles' display on the "Boston Arm" improved the subject's accuracy in all but one case. It improved his precision in every case.

When sound was occluded the feedback reduced errors by 50 percent or more. Since limb noise will be reduced by external clothing as well as by design improvements for cosmetic reasons, supplementary kinesthesis through the tactile feedback will become more important.

Varying terminal device load did not significantly affect positioning performance. The force proprioception built into the servo-mechanism apparently causes the subject to compensate correctly. A more dramatic test of the role of the force sensing feedback might be to undertake tests with the force feedback completely deactivated, thereby establishing the absolute contribution of force proprioception. For the tests herein conducted, even with zero terminal device load, the subject must generate sufficient EMG to oppose the torque due to the gravitational weight of the limb forearm, which is equivalent to about 300 grams at the terminal device.

In comparison with the standard mechanical prostheses the EMG limb with feedback achieves virtually identical kinesthetic performance.

The display is completely compatible with the EMG control, causes no discomfort to the wearer and is not significantly degraded by the environmental condition of the limb socket. (However, since the READ only test indicated significantly higher performance than tests conducted when wearing the prosthesis, the limb and not the display limits even higher accuracy and precision performance by the amputee.)

Thus, the "Boston Arm", equipped with the Alles' display, achieves all of the volitional, efferent control and conveniences of EMG activation and external power in combination with the positioning sense of the traditional mechanical prosthesis.

Acknowledgements

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REFERENCES

1. Mann, Robert W., "Efferent and Afferent Control of an Electromyographic, Proportional—Rate, Force Sensing Artificial Elbow with Cutaneous Display of Joint Angle", *Proceedings on The Basic Problems of Artificial Prehension, Movement and Control of Artificial Limbs*, London, October 1968.
2. Reimers, Stephen D., "The Testing and Evaluation of a Kinesthetic Feedback System for Amputees", S. M. Thesis, Mech. Eng. Dept., M.I.T., June 1969.
3. Alles, David S., "Kinesthetic Feedback System for Amputees Via the Tactile Sense", Sc. D. Thesis, Mech. Eng. Dept., M.I.T., January 1968. Also abstracted in the *Proceedings of the Second Canadian Medical and Biological Engineering Conference*, Toronto, September 1968.