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# Evaluating manual control devices for those with tremor disability*

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**Abstract**—Tremor disabled subjects were tested in two dimensional tracking tasks. The subjects had action tremor due to various etiologies. Both continuous and discrete targets were used. Displacement sensing and force sensing joysticks were compared. The effect of filtering of the control signal was evaluated. Position and velocity control were compared. While individuals were found to benefit from various combinations of control setups, no single control modification or combination of modifications was beneficial to all. It remains necessary to adapt manual control interfaces to the needs of the individual disabled person. Most customizing can be implemented with software.

## INTRODUCTION

From a clinical standpoint, the management of abnormal involuntary movement is a worthwhile target for research because of the substantial numbers of people involved, because of the potential for return of function, and because of the intractability of many cases to conventional modes of treatment. Abnormal involuntary movement is seen in cerebral palsy, multiple sclerosis, Parkinson's disease, Friedreich's ataxia, chronic alcoholism, cerebellar injury, monosymptomatic essential tremor, and other congenital, acquired, and degenerative neurological conditions.

The work described in this report is aimed specifically at investigating the effects of joystick interface characteristics on control accuracy in the presence of pathological "intention tremor." This abnormality, commonly seen in people with lesions of the cerebellum and basal ganglia, due, for example, to multiple sclerosis, may be defined as a rhythmic oscillation of a limb induced or aggravated by attempted voluntary movement. In severe cases, its amplitude may be comparable to purposeful acts, so that loss of independent function may be complete. The frequency of oscillation is dependent on the limb segment studied, but frequencies in the 2 to 6 Hz range are typical. Higher frequency physiological tremor (9–11 Hz) is seen in all individuals and has been observed by workers in this laboratory to coexist with the lower frequency intention tremor (1). In earlier work of the authors and their colleagues (2,11) it was observed that intention tremor contaminates voluntary activity in a simple additive way, so that, for example, voluntary tracking of a periodic target movement may be extracted from movement records by ensemble averaging triggered in synchrony with the target. Intention tremor may be disabling in spite of functionally adequate strength.

## HYPOTHESIS

As detailed below, this research is investigating both mechanical properties and signal processing

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aspects of control interfaces. The expectation that tremor may be modified by these means arises from several sources. Adjustment of the spectral content of normal control of limb position by manipulation of the visual display through which the task is presented has been demonstrated (16). Normal physiological tremor has also been shown by numerous authors (7,10,14,15) to be adjustable in amplitude and frequency by application of inertial and elastic loads. While far less frequently reported, modulation of pathological tremor has also been observed both clinically (5) and experimentally (3,9). The present authors and colleagues have reported experiments in which viscous damping was successful in producing selective reduction of intention tremor during one degree-of-freedom tracking tasks (1,2,11).

The feasibility of mechanical modification of tremor is also suggested by hypothetical tremorgenic mechanisms. Systems theory suggests three models or contributing phenomena. The biomechanical resonance hypothesis (8) treats the muscle-limb plant as an underdamped spring mass system with tuned oscillations driven by broad-band muscle force oscillations. Closed neuromuscular loops, e.g., spinal reflexes, are also capable of unstable oscillations (12,17), especially considering the presence of delay elements and pathologically increased gain. Simplest of all, a central nervous system "oscillator" may drive the neuromuscular loops at the observed tremor frequencies (4,6). At this point, the work of the authors and colleagues suggests a dominant role for the third mechanism in the generation of intention tremor (1).

Under each of these hypotheses, mechanical loading is a rational approach. Applied loads may be viewed either as a potential source of series compensation for loop oscillators or mechanical filtering given a central drive. Isometric restraint coupled with force sensing eliminates the limb mass term from the biomechanical plant, reducing the system order and hypothetically eliminating the possibility of resonance.

## METHODOLOGY

Test subjects were required to perform a series of visual target tracking tasks in two dimensions. The tests were performed using the experimental setup shown in **Figure 1**. The subject was seated facing a 10 cm by 10 cm display on which the target and cursor appeared (**Figure 2**). The joystick was rigidly mounted in such a way that height and attitude could be adjusted. The weight of the subject's forearm was supported by a feeding assist orthosis which permitted low friction movement in the hor-

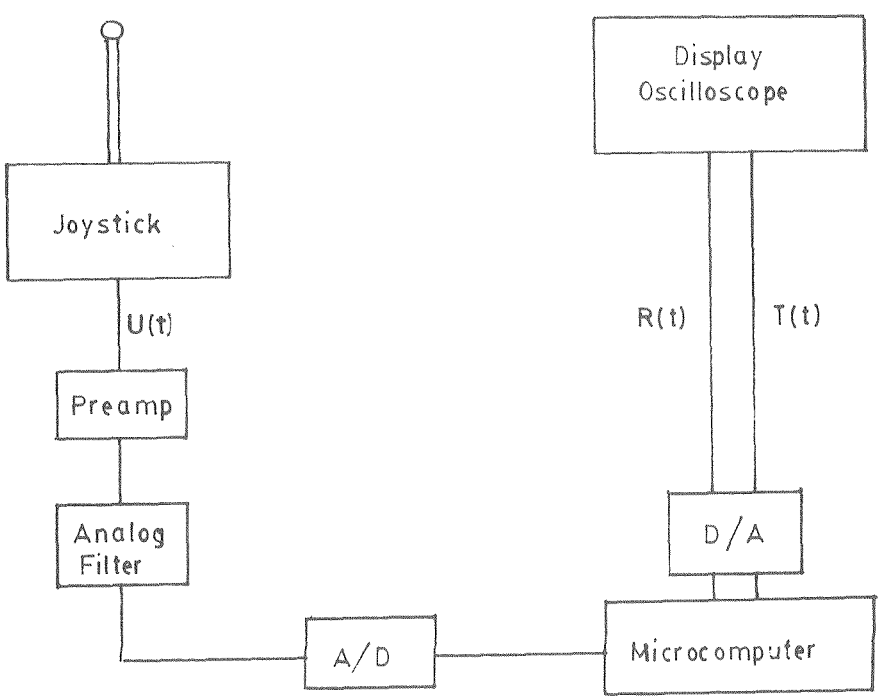



**Figure 1**
Test Setup: U(t) = Input, R(t) = Response, T(t) = Target

izontal plane and rotation in the vertical plane about the forearm support point. This arrangement minimized subject fatigue and provided a degree of trial-to-trial uniformity in the way the joystick was grasped. The subject was otherwise unconstrained.

The microcomputer used, an ADAC system 2000, incorporates A/D and D/A capability. Two joysticks were used, a two axis force sensing joystick (Measurement Systems, Inc., 435 DC) with a stiffness of 0.0014 mm/newton and a displacement joystick (Measurement Systems, Inc., 521T) modified by eliminating the return springs. An 8th order analog Butterworth antialiasing filter with a 14 Hz cutoff (0.35 x sampling frequency) was employed. This frequency permitted observance of higher frequency (9–11 Hz) tremor if present. The target signal, T(t), generated by software in real-time, was designed to appear to be random.

For each type of tracking task a number of parameters were used to evaluate subject performance. The continuous target tracking error was defined as:

$$\Delta H_{TR} = 1.0 - H_{TR} \qquad [1]$$

where $$H_{TR} = \int G_{TR}(\omega)\, d\omega / \int G_{TT}(\omega)\, d\omega \qquad [2]$$

and $G_{TR}$ and $G_{TT}$ are cross and auto power spectra, and the integrals are evaluated over the frequency band of target power (less than approximately 2 Hz). Thus $H_{TR}$ is a measure of the average tracking transfer function. The tremor power was defined as:

$$P_{\tau} = \int G_{RR}(\omega)(1 - \gamma^2_{TR}(\omega))\, d\omega \qquad [3]$$

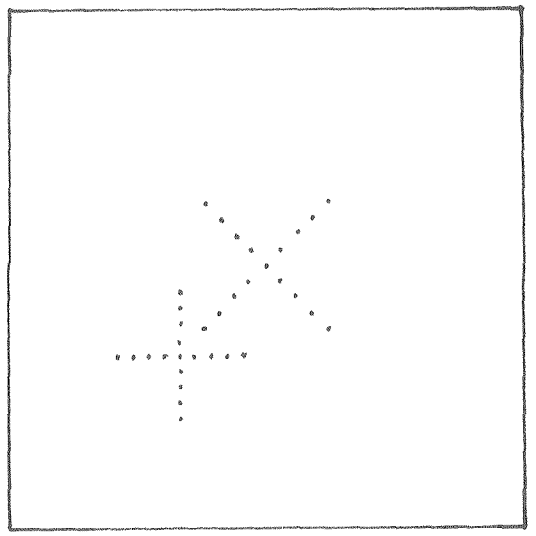
where $\gamma^2_{TR}$ = coherence of the target and response.

$G_{RR}$ = the response auto power spectrum.

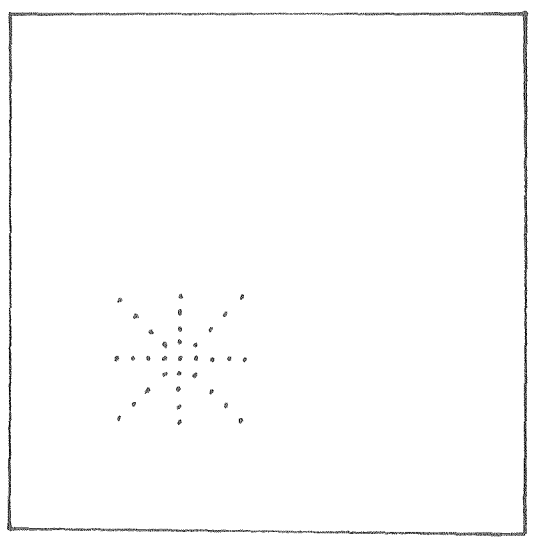
Here the integral was evaluated from 2 Hz to the antialiasing filter frequency (~14 Hz). The signal to noise ratio was defined as:

$$SNR = \int G_{TR}(\omega)\, d\omega / P_{\tau} \qquad [4]$$

where the integral was evaluated over the frequency band of interest. The denominator is defined above and represents the power associated with "noise," i.e., with tremor. The numerator is the power



a. Target-lower left
Response-on center



b. On Target

**Figure 2**
CRT Display

associated with the portion of the response linearly related to the target.

A control effort factor was:

$$E = \int U^2(t)\, dt / \int T^2(t)\, dt \qquad [5]$$

where $T(t)$ is the target signal measured in screen units and $U(t)$ is the joystick output voltage (see **Figure 1**). This index provides a measure of the "cost" of the achieved tracking performance in the presence of each interface and processing scheme in terms of interface output signal power.

The condition of stationarity which must be met to employ the spectral averaging techniques used to evaluate these performance parameters is met because the subject's response is made up of two components, each of which is stationary under the conditions of these tests. Ideally, the target tracking component follows the target closely. The target was designed to be stationary with a zero mean over the trail and over the briefer periods during which individual FFT's were computed for averaging. The individual trials were designed to be sufficiently brief so as not to exceed the subject's attention span, assuring reasonably consistent tracking. Subjects whose data showed a trial-to-trial variation of $H_{TR}$ indicating learning effects or decreased attention were excluded from analysis. While Stiles (13) has shown that the frequency and amplitude of normal hand tremor vary over periods on the order of an hour, Adelstein (1) has shown intention tremor to be stationary over periods comparable to the trial length.

For the discrete target tracking trials the parameters measured were referred to as Settling Rate, Settling Time, Acquisition Rate, Response Time, and Error Power. Settling Rate ($R_S$) was defined as the fraction of target position transitions for which the response came within and remained within +20 percent of the transition magnitude of the target for at least the last 0.5 seconds of the allotted period (approximately 6.5 seconds). Settling Time ($T_S$) is the time from target transition to arrival of the response within the ±20 percent band for those cases where "settling" occurred. Acquisition Rate ($R_A$) is the fraction of target transitions in which the response remained within ±20 percent band for at least 0.5 seconds during the period. Acquisition Time ($T_S$) is the time from target transition to the beginning of acquisition. Error Power ($P_E$) was defined as the average of the square of the target to response distance from the beginning of the first acquisition until the end of the period (time of the subsequent target transition). **Figure 3** illustrates the meaning of acquisition, settling, and the associated times. (Note that settling implies acquisition, but acquisition does not imply settling.) If the response shown in **Figure 3** had remained within the range after acquisition, the acquisition and settling would have occurred at the same time ($T_A = T_S$).

The experimental design is represented in **Figure 4**. This testing protocol permitted the direct comparison of: 1) performance with filtering to performance without filtering, 2) performance using velocity control to performance using position control, and 3) performance using a force sensing device to

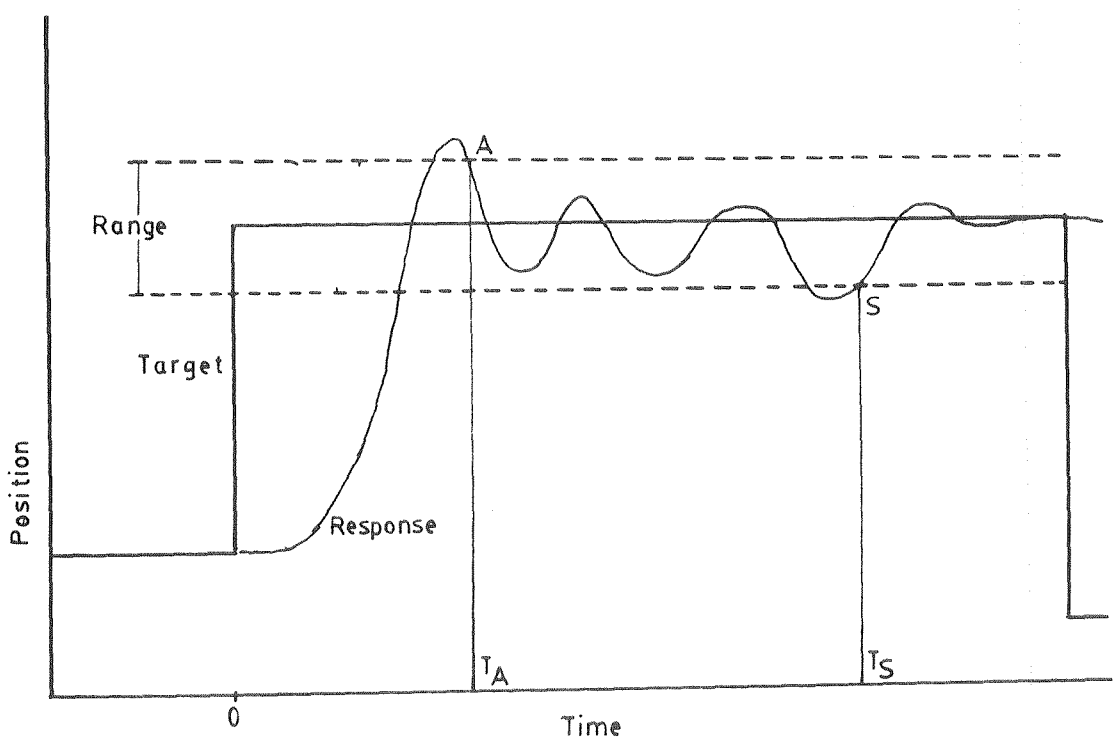



**Figure 3**
Settling (S) and Acquisition (A) Illustrated: $T_A$ = Acquisition Time, $T_S$ = Settling Time

performance using a displacement device. Velocity control implies that the response cursor position is controlled by the time integral of the input signal U(t); position control implies that the response cursor position is dirctly proportional to U(t). Since velocity control is a form of filtering, the combination was considered redundant and not included.

The experimental protocol was the same for each device and essentially the same with slight variation with respect to total number of trials for all subjects. For each interface and control mode the subject was allowed to familiarize himself/herself with the setup. The subject then practiced tracking for several runs with each target type.

The subject then performed four to six tasks with each target type and control alternative. Each task lasted approximately 45 seconds, with 25 seconds of data taken from the middle of the record. Trials were run at about two minute intervals.

Testing with a given interface lasted approximately one hour. It was sometimes necessary to conduct the tests in more than one sitting to avoid subject physical and/or mental fatigue. In these cases the protocol was divided by interface device but with some trials of each type with each interface performed on each occasion to permit evaluation of performance stability.

## RESULTS

Six subjects were evaluated. **Table 1** lists five of the subjects by initials and shows the etiology of their tremor. The subjects are ordered according to decreasing severity of tremor as measured by the mean SNR for the reference condition (continuous target, unfiltered position control, displacement joystick). The tremor of the sixth subject, C.R.S., was due to a midbrain stroke. This subject was not evaluated for continuous target tracking. Normals achieved SNR's of greater than 20 for the reference condition.

The tables which follow summarize the test results. Three comparisons were made: 1) performance with and without low-pass filtering of the joystick output (**Table 2**); 2) performance using

**Table 1**
Subject Information

| Subject | SNR | Tremor Etiology |
|---|---|---|
| JAG | 1.314 | Head Injury |
| RVM | 1.799 | Multiple Sclerosis |
| RBT | 7.886 | Head Injury |
| JBG | 12.774 | Cerebellar Ataxia |
| EPS | 13.452 | Cerebral Palsy |

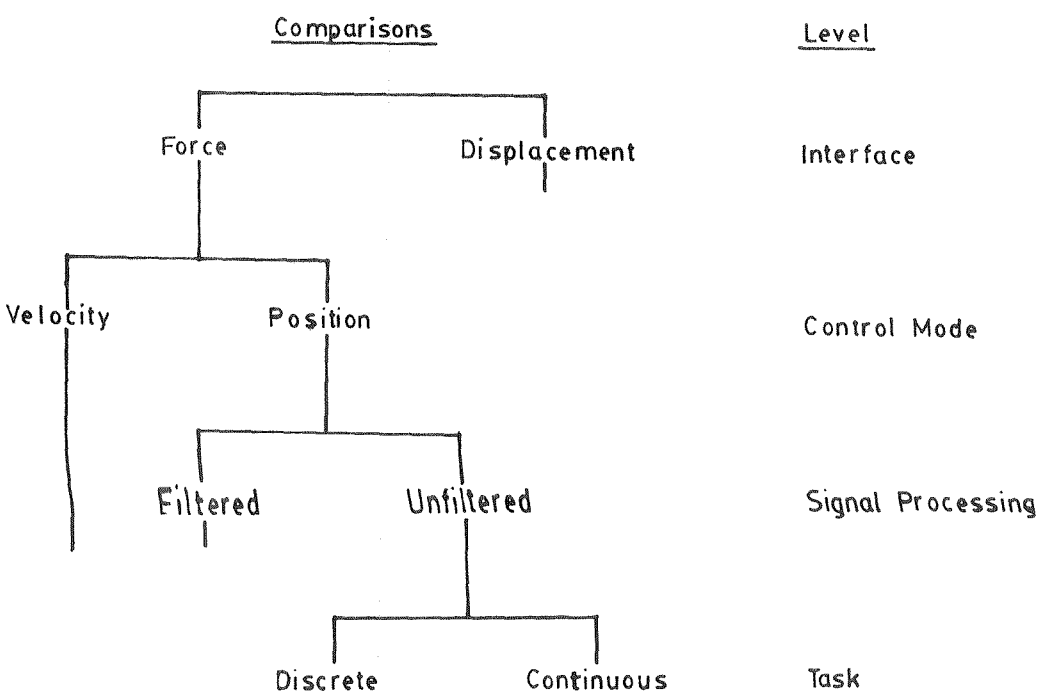



**Figure 4**
Experiment Design Tree

velocity control versus performance using position control (**Tables 3 and 4**); and 3) performance using a force sensing (isometric) joystick compared to performance using a displacement sensing joystick (**Tables 5 and 6**). Each result is given as a three-number cluster where the upper left hand number indicates the number of subjects who achieved an improvement in the performance parameter in question (at a probability level $p<0.1$); the upper right hand number indicates the number of subjects whose performance measured by the parameter deteriorated ($p<0.1$); and the lower number indicates the total number of subjects tested for the set of conditions in question. "Improved performance" means that the parameter in question changed in the desired direction, i.e., higher SNR, lower tremor power, shorter settling time, etc. The probability level p is based on unpaired t-tests of the difference of the means of each parameter for all trials with the given set of conditions.

The results of filtering for continuous target tracking are summarized in **Table 2**. These results are consistent with the hypothesis that filtering can improve SNR by reducing the tremor component of the control signal. While no negative effects are associated with the 4 Hz filtering, degraded performance is seen with the lower cutoff frequency. An example of filtered and unfiltered tracking is presented in **Figure 5**. The effect of filtering on the tremor power spectra is shown in **Figure 6**. In the case of discrete target tracking little likelihood of achieving an improvement with filtering is demonstrated. However, there was a fairly consistent increase, i.e., degradation, of acquisition and settling times when the 2 Hz filtering was used reflecting the slower response of the filtered system.

When the velocity control was compared to unfiltered position control, the results, shown in **Table 3**, indicate that, like filtering, velocity control also improves SNR by attenuating the tremor component of the input. Velocity control has a beneficial effect on SNR in a higher percentage of subjects with the force sensing joystick than with the displacement joystick. Velocity control frequently entails a penalty in tracking quality and control effort. **Figure 7** shows a comparison of tracking with velocity control and tracking with unfiltered position control.

**Table 2**
Filtering Effect Continuous Tracking, Position Control

| | SNR | P | $H_{TR}$ | E |
|---|---|---|---|---|
| 4 Hz filtering vs. unfiltered, force sensing | 1/0 / 4 | 1/0 / 4 | 0/0 / 4 | 0/0 / 4 |
| 2 Hz filtering vs. unfiltered, force sensing | 1/0 / 2 | 0/1 / 2 | 1/1 / 2 | 0/2 / 2 |
| 4 Hz filtering vs. unfiltered, displacement sensing | 2/0 / 5 | 1/0 / 5 | 0/0 / 5 | 1/0 / 5 |
| 2 Hz filtering vs. unfiltered, displacement sensing | 2/0 / 2 | 1/0 / 2 | 0/0 / 2 | 0/0 / 2 |

**Table 3**
Velocity Control Effect Continuous Tracking, Unfiltered

| | SNR | P | $H_{TR}$ | E |
|---|---|---|---|---|
| Force Sensing | 3/0 / 4 | 3/0 / 4 | 1/1 / 4 | 0/3 / 4 |
| Displacement Sensing | 1/0 / 5 | 1/0 / 5 | 0/5 / 5 | 0/4 / 5 |

**Table 4**
Velocity Control Effect Discrete Target Tracking, Unfiltered

| | $R_A$ | $R_S$ | $T_A$ | $T_S$ | $P_E$ |
|---|---|---|---|---|---|
| Force Sensing | 3/0 / 5 | 1/0 / 5 | 0/1 / 5 | 2/1 / 5 | 1/0 / 5 |
| Displacement | 0/0 / 6 | 0/0 / 6 | 0/1 / 6 | 0/2 / 6 | 0/1 / 5 |

**Table 5**
Force vs. Displacement Sensing Continuous Target Tracking, Unfiltered

| | SNR | P | $H_{TR}$ |
|---|---|---|---|
| Position Control | 1/2 / 4 | 1/1 / 4 | 0/4 / 4 |
| Velocity Control | 1/0 / 4 | 2/0 / 4 | 1/1 / 4 |

**Table 6**
Force vs. Displacement Sensing Discrete Target Tracking, Unfiltered

| | $R_A$ | $R_S$ | $T_A$ | $T_S$ | $P_E$ |
|---|---|---|---|---|---|
| Position Control | 0/2 / 5 | 0/1 / 5 | 0/0 / 5 | 1/2 / 4 | 0/3 / 5 |
| Velocity Control | 0/0 / 5 | 0/3 / 5 | 0/0 / 5 | 2/0 / 5 | 0/1 / 5 |

**Table 4** presents the comparison of velocity control with position control for discrete target tracking. Velocity control improved $R_A$ and $R_S$ for some subjects with force sensing but was never beneficial when used with the displacement device. $T_A$ and $T_S$ were frequently longer with velocity control.

**Tables 5 and 6** compare performance using the force sensing joystick to performance using the position sensing joystick. Control effort (E) is not presented because force generating effort and displacement generating effort were not directly comparable under the test conditions. Performance often improves with the force sensing device, but degraded performance is more common.

For the trials in which the effect of filtering was being evaluated, the visual display presented to the subject reflected the filtered version of the subject's response. It was, therefore, possible that the subject controlled the filtered response in a different way than he/she controlled the unfiltered response, producing a result different from that which would be predicted for application of the filter outside the visual feedback loop. This question was addressed by a three-way comparison: performance with filtering present on-line (effect visible to the subject), performance without filtering, and performance with filtering performed off-line (not fed back to the subject). Off-line filtering trials were generated by

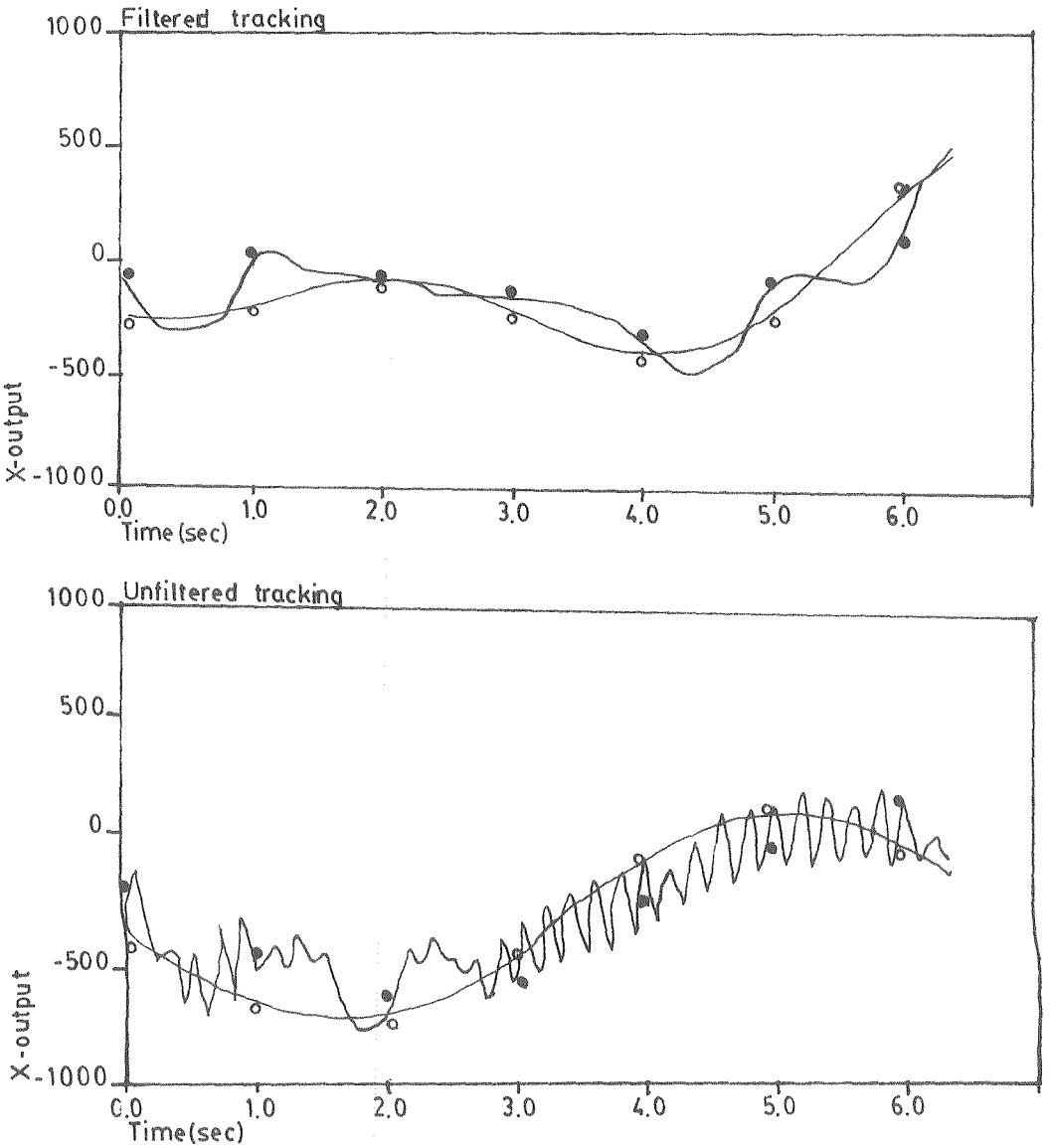



**Figure 5**
Filtered and Unfiltered Tracking: ● response, ○ target

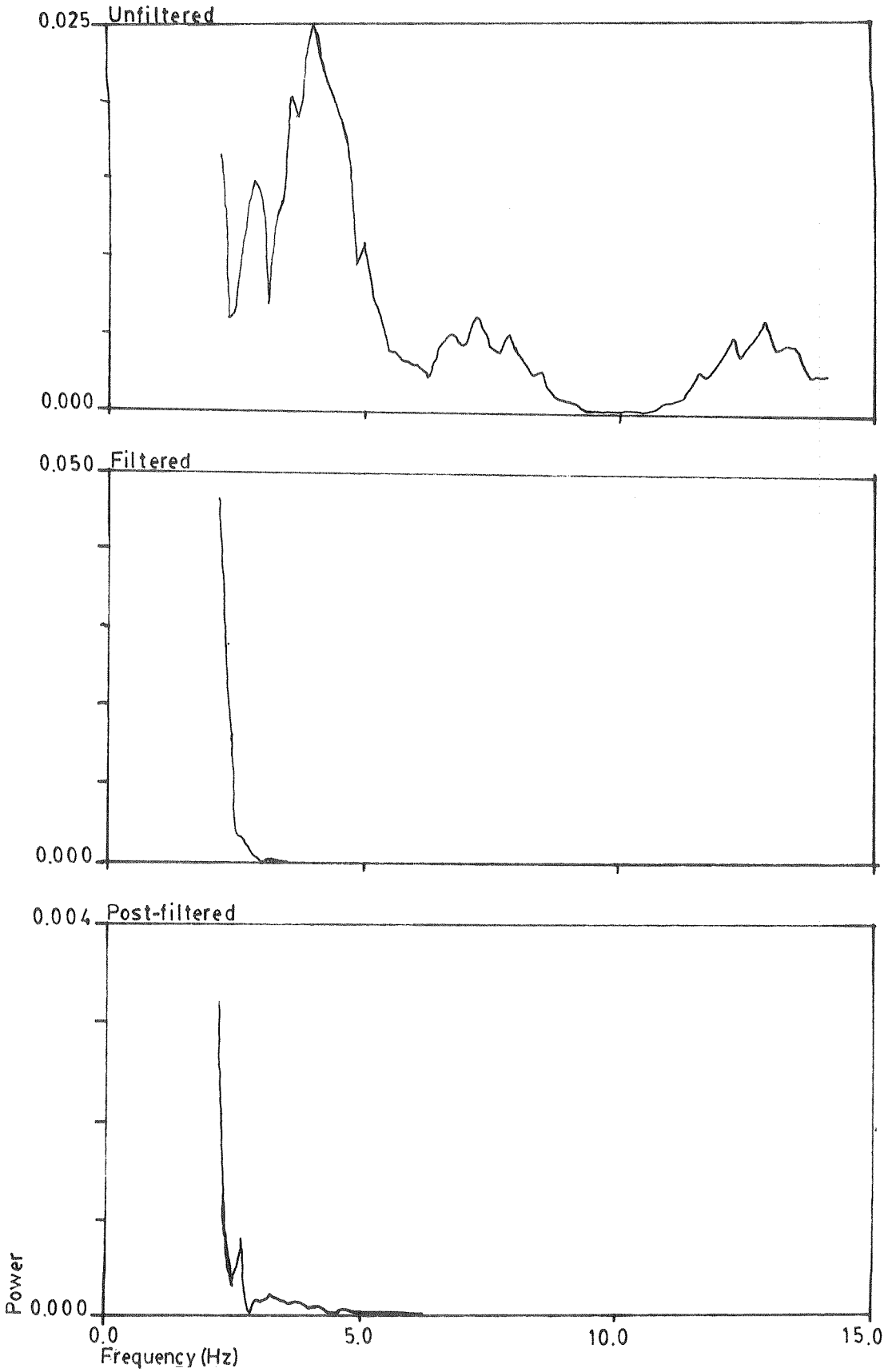



**Figure 6**
Subject RVM, unfiltered, filtered, and post-filtered tremor power spectra

post-filtering the input, U(t), recorded during unfiltered trials with digital filters matched to the filters used on-line.

In general, performance with on-line filtering was equal to performance with off-line filtering ($p>0.9$). In a few cases the subjects performed better with on-line filtering than would have been predicted by off-line filtering. The performance of one subject with a 2.5 Hz on-line filter was not as good as predicted by off-line filtering.

The effect of varying the gain for position control with the force sensing device was tested with four subjects. Previous work with isometric force sensing control devices (1) had indicated that SNR improved with decreased gain, i.e., as more voluntary torque was required for a given display excursion. The hypothesized mechanism for this effect was that the amplitude of force tremor remained essentially constant while the total force level increased, resulting in an increase in the signal (voluntary force) to noise (tremor force) ratio. This has been observed for isometric torque generation about a single joint, the wrist (1). The purpose of this test was to see if a similar overall efffect could be obtained in a less constrained, more functional control setup.

**Table 7** presents the results of a linear regression through the gain test data. In general, a negative correlation of SNR with gain was found, consistent with the hypothesis that lower gain results in a higher SNR. The minimum gain must, of course, be

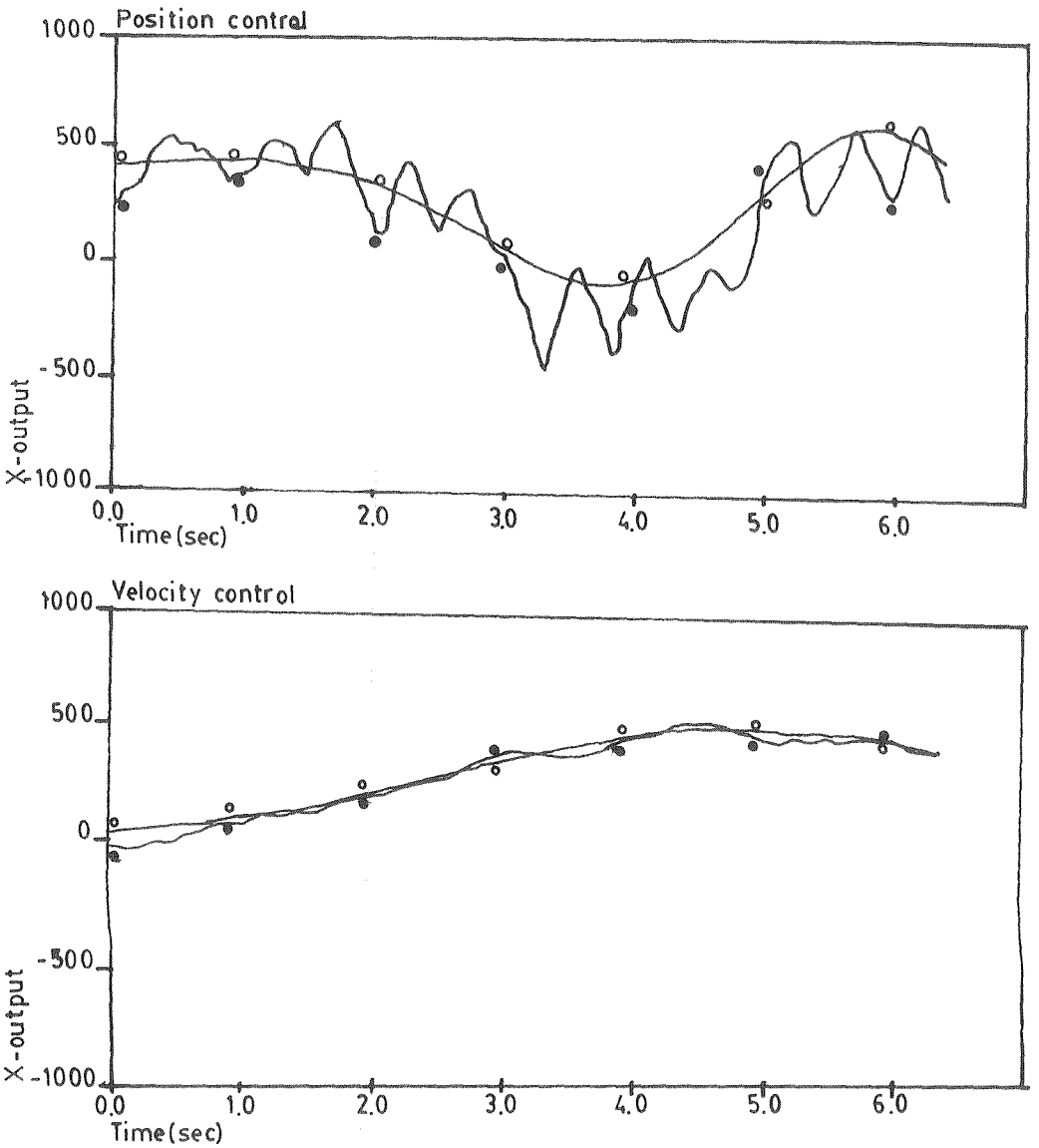



**Figure 7**
Position and velocity control tracking: ● response, ○ target

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**Table 7**
SNR vs. GAIN (Normalized) Force Sensing, Unfiltered Position Control

| Subject | Intercept | Slope | Significance Level (P) | F | $R^2$ |
|---|---|---|---|---|---|
| JBG | 1.809 | −.809 | .218 | 1.6 | .09 |
| EPS | 1.302 | −.302 | .075 | 3.95 | .283 |
| RVM | 1.065 | −.271 | .014 | 19.76 | .523 |
| RBT | .784 | .216 | .461 | .5811 | .0462 |

*F = Ratio (Between Mean Square)/(Within Mean Square); $R^2$ = Fraction of Variability Explained, Correlation Coefficient Squared.

such that the subject is able to achieve full scale deflection with a reasonable fraction of maximum voluntary effort. For subject R.V.M., whose SNR decreased most significantly with increasing gain, both the tremor power and tracking error increased with gain. For this same subject a linear regression of input tremor against gain also showed a positive slope. This indicates that tremor, if it increases at all with increased effort, increases more slowly than total effort.

Besides the range of tremor etiologies and the expected variance of individual performance, another factor which might have accounted for some of the variability in performance improvement achieved with the various techniques tested was the subject-to-subject variation in the severity of tremor. Ranking the subjects by tremor severity, however, showed that neither the improvement nor the worsening of performance seemed to cluster at either end of the tremor severity spectrum. In other words, the likelihood of achieving an improvement in performance is not particularly related to the severity of the tremor. Since more severe tremor is more disabling, any improvement achieved probably implies greater restoration of function.

## DISCUSSION

The comparisons of filtered with unfiltered processing, velocity with position control, and force with displacement sensing do not demonstrate consistent effects that would permit predicting that a given technique would benefit all users. However, it was shown that each of the techniques can be beneficial to certain individuals. Variation among individuals, or perhaps among tremor etiologies, may ultimately make it necessary to assess each individual in order to prescribe an appropriate interface and control mode.

For example, the results for subject R.V.M. displayed in **Table 8** show that both 4 Hz filtering and velocity control are effective in improving SNR. This subject also performed better with the force sensing device than with displacement sensing. The poor results achieved with the 2.5 Hz filter are of interest and will be discussed below. This subject would benefit from 4 Hz filtering if using a displacement sensing joystick and position control. He might also benefit from a force sensing device with velocity control in situations where accuracy constraints were not severe and fatigue was not an issue.

Filtering was expected to improve SNR by reducing the tremor component of the response signal ($P_\tau$) without affecting the control error ($\Delta H_{TR}$). The results indicate that where an improvement in SNR is achieved, there is in fact a decrease in $P_\tau$. $\Delta H_{TR}$ is not always unaffected, however; both increases and decreases in tracking error are seen. Filtering tremor from the displayed response may enhance the subject's ability to detect tracking error, explaining improvements in tracking. This would resolve those cases where performance with on-line filtering was superior to that predicted by off-line filtering.

The decrements in tracking fidelity, i.e., increases in $\Delta H_{TR}$, observed in some filtered trials may be a function of decreased system responsiveness. While the filtering employed did not significantly attenuate the response signal at frequencies corresponding to target power, tracking of a random signal would certainly be facilitated if system bandwidth were greater than target bandwidth. The more frequent occurrence of degraded tracking with the lower filtering cutoff frequency is consistent with this interpretation. Additionally, users may set lower standards for their performance if they consider their device unresponsive. This may have been true in the case of subject R.V.M., whose performance with the 2.5 Hz filter on-line was not as good as off-line filtering predicted.

Where velocity control resulted in an improvement in SNR, this was accomplished by reducing the P component of the response signal. Velocity control also frequently resulted in increased tracking error ($\Delta H_{TR}$) and increased control effort (E) compared to unfiltered position control. Velocity control was generally more successful in conjunction with the force sensing device.

**Table 8**
Subject RVM—Continuous Tracking

| Comparison Variable | Fixed Conditions | SNR | P | $H_{TR}$ | E |
|---|---|---|---|---|---|
| 4 Hz Filtering vs. Unfiltered | Force Sensing Position Control | = | = | = | = |
| | Displacement Sensing Position Control | + | + | = | + |
| 2.5 Hz Filtering vs. Unfiltered | Force Sensing Position Control | – | – | = | – |
| Velocity vs. Position Control | Force Sensing Unfiltered | + | + | – | – |
| | Displacement Sensing Unfiltered | + | + | – | – |
| Force vs. Displacement Sensing | Position Control Unfiltered | + | + | – | * |
| | Velocity Control Unfiltered | + | + | – | * |

*Not compared

The best SNR for the combination of force sensing and position control is achieved when the gain in minimized within limits set by the subject's strength. While the question of fatigue was not quantitatively addressed during these tests, it seems likely that there would have to be a tradeoff between the improvement in accuracy achieved and the increased level of work required by the subjects.

## CONCLUSIONS AND RECOMMENDATIONS

The study did not indicate that any of the system features evaluated could be expected to allow optimal tracking performance for all tremor disabled persons. It did, however, suggest that, on an individual case basis, a feature or combination of features can be found to exist which result in improved tracking with respect to performance with the "standard interface," i.e., displacement sensing and unfiltered control of position. Equally important is the result that for each individual, some system features can result in seriously degraded performance relative to the standard interface. This highlights the need to evaluate clinically a broad range of control system configurations to find the one best suited to the individual patient. All testing was done with a single computer system and a very limited amount of special hardware, demonstrating that it is possible to evaluate performance with systems of varying characteristics by evaluating them with a single readily available and inexpensive assessment tool. The importance of assistive devices which are themselves programmable and thereby customizable was also suggested.

Further study is needed in several areas. Control via isometric force sensing seemed to improve with decreased system gain, but the effect of fatigue on performance with a low gain system needs to be evaluated. The improved SNR with velocity control seemed to be obtained at the expense of less accurate tracking for most subjects, but it would certainly be of interest to see if this could be corrected by practice and skilled coaching. If so, the improvement in SNR seen with velocity control would be more significant.

This study has demonstrated that control accuracy of tremor disabled persons can be improved by the selection of suitable interface characteristics. The testing necessary to select the most favorable characteristics requires only a brief (about 1 hour) protocol which can be implemented in software on any laboratory computer, including the now standard PC compatibles. This should provide clinical engineers with a valuable tool in their efforts to assist persons with this severe disability.

### Acknowledgments

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