LINEARITY OF HUMAN COMMANDS FOR TELEROBOTICS

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ABSTRACT

We identify frequency limitations on linearity in two-dimensional (2-D) motion for three subject groups: young (mean and σ: 23±3), old (72±2), and movement-disabled (65±16). The linearity of the relationship between input and output--i.e., between target tracking signals and resulting human upper extremity motion--is quantified using adaptive coherence estimation. We show that linearity decreases with input frequency. Old and disabled subjects' 2-D motion is almost completely nonlinear. Nonlinear filtering therefore will likely improve precision in rehabilitative and surgical teleoperation.

I. INTRODUCTION

Determination of the intended command given to a man-machine system when noise is present is essential for rehabilitative [1] and surgical [2] teleoperation. In this work, we treat the human teleoperator as a system for which the input is visual sensation and the output is transducted arm movement. We measure the linearity of human motion with respect to command intent at different frequencies. This data informs us how to better extract intended commands of the human from actual motion transducted by the machine.

II. METHOD

A. Experiments

We used a mouse, sampled at 21 Hz, as a simple, low degree-of-freedom teleoperation platform. Three groups of subjects participated: The *young* group (eight healthy subjects, age 23 ± 3 (standard deviation)); the *old* group (four healthy subjects, age 72 ± 2); and the *disorder* group (five patients: three with essential tremor, one with rubral tremor, and one with anoxic myoclonus, age 65 ± 16).

One-dimensional (1-D) experiment: Subjects generated a sinusoidal motion, attempting to keep a mouse cursor pointing at a moving target block sinusoidally tracing a vertical line 1.3 cm long. Tests were done at eight frequencies (0.4 to 4.6 Hz) for 15 cycles each.

Two-dimensional (2-D) experiment: Subjects generated a circular motion of radius 1.3 cm, matching a similar target. Tests were done at four frequencies (0.4 to 2.6 Hz) for 15 cycles each.

B. Analytical method

Let t be the input signal, and o the human output. Coherence has been defined as

$$\gamma_{to}(f) = \frac{G_{to}(f)}{\sqrt{G_{tt}(f)G_{oo}(f)}} \quad (1)$$

where G is a power density spectrum. It has been used to quantify linear association between two signals [3].

Kong and Thakor [3] presented a linearity index, LI, that robustly indicated whether t and o were linearly related:

$$LI = \frac{1.0}{1.0 + \sum_i \Phi\left|(\hat{\gamma}(f_i,k) - 1.0)\right|} \quad , \quad (2)$$

where the f_i were harmonics (i=1 was used), $\hat{\gamma}$ was the estimate of γ, F(x) was a threshold function defined as

$$\Phi(x) = \begin{cases} 0.0, \text{ if } x < 0.2 \\ x, \text{ if } x \geq 0.2 \end{cases} \quad , \quad (3)$$

and k was a time index. An LI value of 1 indicated a perfect linear system, while a smaller value indicates a proportionate degree of nonlinearity. LI results were computed per input cycle using a least-squares technique [3] and then averaged.

III. RESULTS

The results for the 1-D and 2-D tests were as shown in Figures 1 and 2 respectively. In the 1-D tests, only the first point of the young group was significantly higher than the other groups ($p<.05$). For the 2-D tests, differences were significant ($p<.05$) at all points between the young and disorder groups, and at 0.4 and 0.8 Hz between the old and disorder groups. For both the 1-D and 2-D experiments, results from the old group and the disorder group were always lower than those from the young group, although in many cases these differences were not significant. The disorder group 2-D data contained no significant linearity ($p<.05$).

IV. DISCUSSION

Significant nonlinearity is present in all data ($p<.05$). The usefulness of linear filtering for extraction of human intentions from teleoperative interfaces is limited by this nonlinearity. Rehabilitative and surgical teleoperation can be improved by the modeling and removal of this nonlinear component. Nonlinear filtering is therefore important for precise teleoperation.

V. CONCLUSIONS

The relationship between human intention and actual upper extremity motion is in general nonlinear. The linearity of human motion decreases as intended movement frequency increases. Factors such as advanced age and movement disorders may cause more pronounced nonlinearity.

ACKNOWLEDGMENTS

Funding provided by NIDRR (grant H133G30064). Thanks to Dr. S.G. Reich, Dr. H.F. Rizer, and M. Fung.

0-7803-2050-6/94 $4.00 ©1994 IEEE

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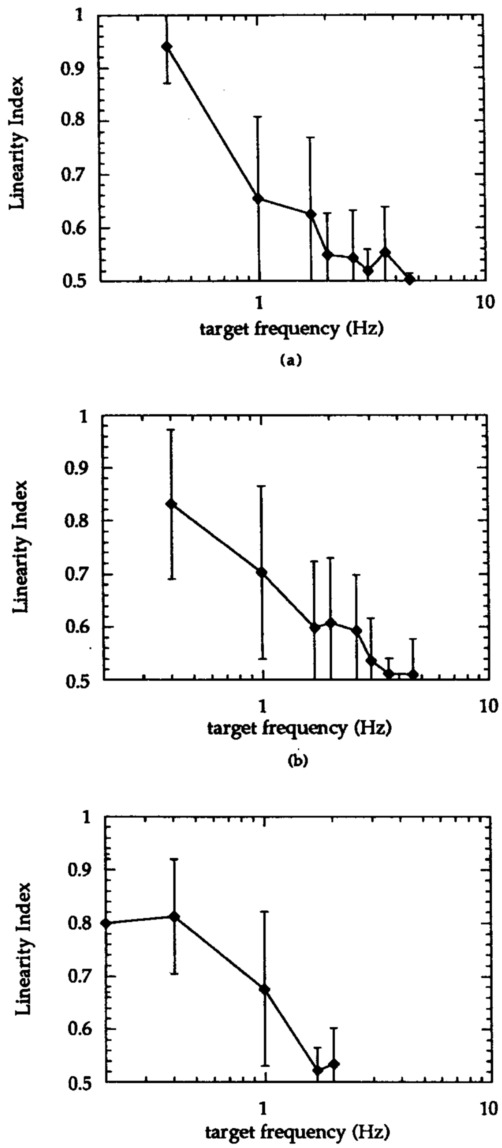

Figure 1. *LI* for 1-D experiment. (a) Young group (n=8). (b) Old group (n=4). (c) Disorder group (n=5). Plots indicate mean ± standard deviation. For all groups, linearity generally decreases with increasing input frequency. All groups approach complete nonlinearity at high input frequencies.

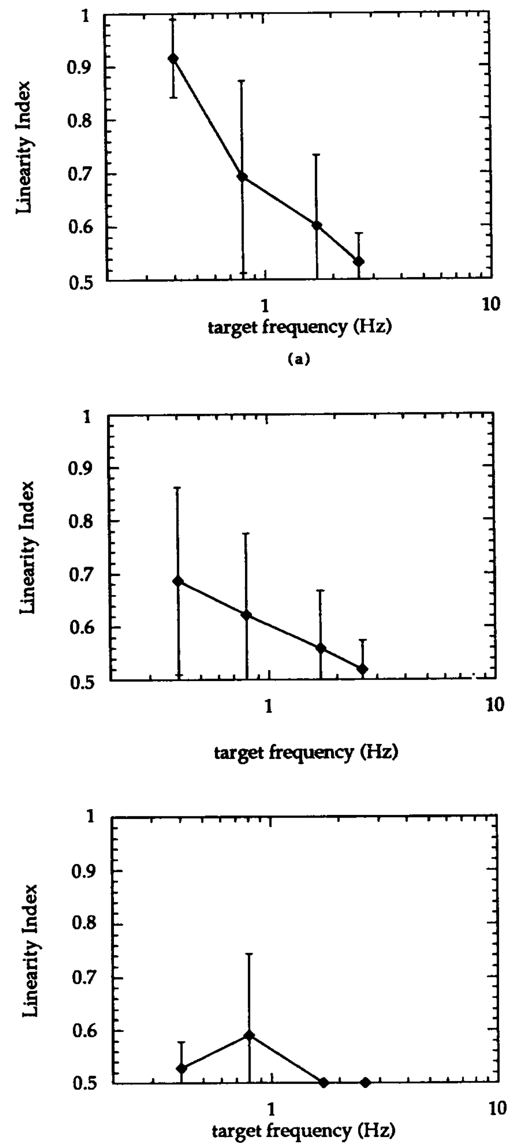

Figure 2. *LI* for 2-D experiment. (a) Young group (n=8). (b) Old group (n=4). (c) Disorder group (n=2). Plots indicate mean ± standard deviation. Note that the old and disorder groups are almost always within 1 standard deviation of 0.5, which indicates complete nonlinearity.