Assessing Vibrotactile Feedback Strategies by Controlling a Cursor with Unstable Dynamics

Kristin M. Quick, *IEEE Student Member*, Nicholas S. Card, Stephen M. Whaite, *IEEE Student Member*, Jessica Mischel, *IEEE Student Member*, Patrick Loughlin, *IEEE Fellow,* and Aaron P. Batista

Abstract— **Brain computer interface (BCI) control predominately uses visual feedback. Real arm movements, however, are controlled under a diversity of feedback mechanisms. The lack of additional BCI feedback modalities forces users to maintain visual contact while performing tasks. Such stringent requirements result in poor BCI control during tasks that inherently lack visual feedback, such as grasping, or when visual attention is diverted. Using a modified version of the Critical Tracking Task [1] which we call the Critical Stability Task (CST), we tested the ability of 9 human subjects to control an unstable system using either free arm movements or pinch force. The subjects were provided either visual feedback, 'proportional' vibrotactile feedback, or 'on-off' vibrotactile feedback about the state of the unstable system. We increased the difficulty of the control task by making the virtual system more unstable. We judged the effectiveness of a particular form of feedback as the maximal instability the system could reach before the subject lost control of it. We found three main results. First, subjects can use solely vibrotactile feedback to control an unstable system, although control was better using visual feedback. Second, 'proportional' vibrotactile feedback provided slightly better control than 'on-off' vibrotactile feedback. Third, there was large intra-subject variability in terms of the most effective input and feedback methods. This highlights the need to tailor the input and feedback methods to the subject when a high degree of control is desired. Our new task can provide a complement to traditional center-out paradigms to help boost the real-world relevance of BCI research in the lab.**

I. Introduction

Brain computer interfaces (BCI) predominately rely on visual feedback. While new decoding algorithms have improved control and increased the number of simultaneously controlled degrees of freedom [2-4], subjects must continuously watch their effector. However, real arm movements do not rely solely on vision for control, and grasping movements use very little, if any, visual feedback. Many researchers have begun to study non-visual feedback, whether it be rendered through vibrating tactors or intracortical microstimulation. Of the studies using tactile feedback, the feedback signal has represented the grasping force on real [5, 6] or virtual objects [7], when an object is slipping from grasp [8, 9], and dynamics during virtual object manipulation [10-12]. In these studies, subjects used a variety of actions to control their task, including natural arm movements, EMG signals to simulate myoelectric prosthesis use, actual myoelectric prosthesis movements, or EEG signals. Researchers are beginning to investigate how to combine intracortical BCI control with non-visual information [13-16]. Real-world feedback depends intimately on the type of movement the user is making. We sought a task paradigm that could capture the interaction between the subject and his or her environment.

To create a virtual environment in which the interaction between a user and an object can be studied in its essence, we designed the Critical Stability Task (CST), which is based on the Critical Tracking Task introduced by Jex et al. in 1966 [1]. The Critical Tracking Task has been used to assess motor performance during drug use and tele-operation, and to design vibrotactile feedback displays for balance prostheses [17-19]. In the CST, subjects must stabilize a first order unstable linear system. A familiar example of an unstable first order system is compounding interest, whereby the debt grows exponentially over time, and the larger the interest rate, the faster the debt grows. In the absence of external factors (payments, in this example), the account balance can be modeled mathematically by $y(t) = y_0 e^{\lambda t}$ where y_0 is the initial loan, and $\lambda > 0$ is the interest rate. We implemented this model to map the one-dimensional position of a cursor on a screen; without external control, the cursor will rapidly drift off the screen. Subjects were required to maintain the cursor near the center of the screen to the best of their ability. The system was made more difficult to control by gradually increasing the parameter λ over time. We determined the largest λ that subjects could control, λ_C, and examined how that parameter depended on different forms of feedback.

During our task, subjects used either unconstrained hand movements or pinch force to control the unstable system. The position of the unstable system was rendered using visual feedback, two forms of vibrotactile feedback, or not rendered at all. Within each control method, the quality of the feedback rendering was assessed using the CST. Feedback renderings that allowed subjects to control greater instability (larger λ) were better feedback renderings. We found that subjects can use solely vibrotactile feedback to

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K. M. Quick, J. Mischel, and A. P. Batista* are with the Department of Bioengineering, Center for the Basis of Neural Cognition, University of Pittsburgh, PA 15261 USA (*corresponding author email: apb10@pitt.edu).

P. Loughlin, N. S. Card are with the Department of Bioengineering, University of Pittsburgh, PA 15261 USA.

S. M. Whaite is with the Department of Electrical and Computer Engineering, University of Pittsburgh, PA 15261 USA.

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control an unstable system, although control was better using visual feedback. We also found that 'proportional' vibrotactile feedback provided marginally better control than 'on-off' vibrotactile feedback. Our final observation is that there was large intra-subject variability in the effectiveness of input and feedback methods. This highlights the need to tailor the input and feedback methods to the subject when a high degree of control is desired [20].

II. METHODS

A. Overview

Subjects performed the Critical Stability Task wherein they had to compensate for their motor or perceptual errors in order to control an increasingly unstable system. Subjects alternately used two methods to control the system and were alternately provided with four methods of feedback on the system's position.

B. Subjects

We tested 9 healthy subjects between the ages of 18 – 40 years without any history of any motor disorders. The subjects were 4 males and 5 females. All subjects gave their informed consent before being tested using a protocol approved by the Institutional Review Board at the University of Pittsburgh.

C. Implementing CST

Subjects controlled an unstable system *G(s)*, as seen in Fig. 1, whose transfer function is:

$$G(s) = \frac{\lambda(k)}{s - \lambda(k)} \tag{1}$$

where instability $\lambda(k) > 0$ increases at a constant rate of 0.10 rad/second until the subject loses control. After converting the transfer function into state-space representation using observable canonical form, we discretized the continuous system for implementation on a computer:

$$\begin{aligned} x(k+1) &= e^{\lambda(k)T}x(k) + \left(1 - e^{\lambda(k)T}\right)u(k) \\ y(k) &= x(k) \end{aligned} \tag{2}$$

In this representation, $u(k)$ is the input signal to the unstable system at time step k, $x(k)$ is the current state of the unstable system, $y(k)$ is the output of the unstable system, and T is the sampling period in seconds, which was 5ms for force control and 10ms for hand control.

In our experiments described below, subjects interacted with the system in a variety of ways. We recorded the critical instability λ_C when subjects lost control of the system. Loss of control occurred when the unstable system's position surpassed a predetermined threshold, in our case, +/-5cm from the center. As a note, λ_C is robust to different thresholds [1]; once the system becomes unstable, it is only a short period of time until the system would cross any threshold.

In the CST, the subjects received feedback on the position of the unstable system, $y(k)$. For example, when controlling the system with hand movements and the cursor was right of center, the subject had to move his or her hand to the opposite position left of center to stabilize the system.

C. Input Methods to Control System

Subjects were tested using two different control strategies with their dominant hand. Unconstrained hand movements were recorded using motion capture via an Improv system (PhaseSpace Inc., San Leandro, CA) and pinch force was measured using a force sensitive resistor (A201, FlexiForce, Tekscan, Boston, MA). The unconstrained hand movements involved mainly shoulder rotations that moved the hand through approximately 20cm of space. Only the horizontal component of their movement was used as input to the unstable system. A hand position of zero corresponded to a position directly in front of the subject. When subjects used pinch force, we subtracted an offset and multiplied by a gain such that -10cm and +10cm were represented by 0N and 9.3N, respectively.

Subjects initiated each trial by positioning their input signal at zero, whether by moving their hand to this location or generating the pinch force that corresponds to a position of zero.

D. Feedback Methods to Render System

In order to control an unstable system, subjects must have feedback about the system. Four different types of feedback were rendered to the subjects. It is important to highlight that the feedback was about the state of the system, not the position of the hand or force on the transducer. The first feedback method was visual. The position of the unstable system was displayed on a monitor approximately 1m in front of the subject. When the subject used hand movements to control the system, the system's position was displayed along the horizontal axis. When the subject used pinch force to control the system, the system's position was displayed along the vertical axis, to make the

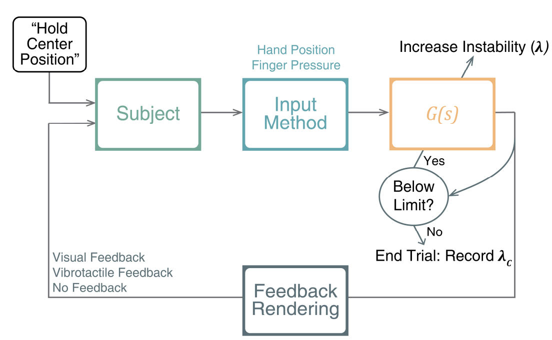

Figure 1 - Diagram of Critical Stability Task. The possible input methods are shown in blue, the unstable system G(s) = λ(k)/(s- λ(k)) in yellow, and feedback rendering methods in gray.

visual feedback more congruent with the control scheme.

The second feedback method was 'proportional' vibrotactile feedback. The system's position was rendered as the vibration intensity of two coin tactors (312-101, Precision Microdrives Limited, UK) on the non-dominate hand which the subject held motionless in their lap. During both hand control and pinch force control, one tactor attached to the thumb to indicate positive deviations and one tactor attached to the pinkie finger to indicate negative deviations.

Subjects oriented their hand with tactors so that the vibrotactile feedback was perceptually congruent to the control method. Thus, for hand control with the right hand, the left hand was palm-down with the thumb to the right of the pinkie. Then for pinch force control, the left hand was rotated vertically so the thumb was above the pinkie. The feedback was not meant to mimic proprioceptive or tactile feedback, but rather to provide information concerning the state of the system. We modulated each tactor's "intensity" using a command voltage that was proportional to the system's position. The tactor's full voltage range was used to maximize amplitude and frequency modulation. An accelerometer attached to each tactor measured the feedback signal. The amplitude and frequency varied together, with amplitudes between 0.5- 12g and with frequencies between 50-170Hz.

The third feedback method was 'on-off' vibrotactile feedback. For any positive deviation of the system, the thumb tactor would vibrate at a fixed intensity near the middle of its operating range. Likewise, the pinky tactor would vibrate at a fixed intensity for all negative deviations. The fourth feedback method was no feedback. Subjects had to attempt to control the system without being given its current position.

F. Experimental Design

Subjects completed one block of trials using pinch force control and one block of trials using hand control. Within each block, subjects completed five consecutive trials of each feedback method in random order, for a total of 40 trials per subject. Subjects had one practice trial before each block where they used visual and vibrotactile feedback. Trials lasted 5-45s depending on the subject's ability to control the system. Subjects had 2s of rest between hand movement trials and 15s between pinch force trials to reduce fatigue. Experimental sessions lasted approximately 35min. To determine the effectiveness of the eight different feedback-control methods, we compared the mean and standard deviation of λ_C using data from all subjects.

III. RESULTS

A. Visual Feedback Results

Fig. 2 shows the mean λ_C scores for each of the eight different feedback-control methods. Subjects achieved a higher λ_C using pinch force control (3.19 ± 0.70) rather than

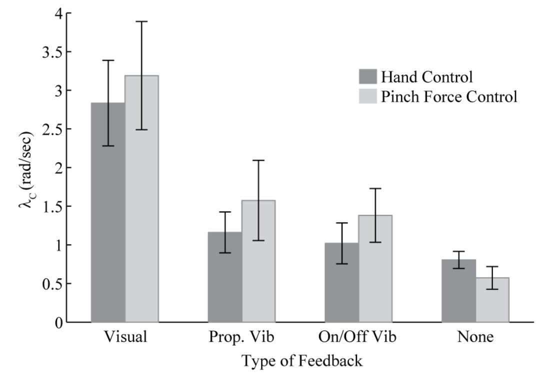

Figure 2 - Mean and standard deviation of λ_C for each feedback-control method shown in TABLE I, calculated using the five associated scores from each subject, for a total of 45 λ_C scores used in each bar.

hand control (2.83 ± 0.55) under visual feedback, as tested by Welch's t-test where the λ_C variance of each feedback-control method is not assumed to be equal ($p = 0.009$).

B. Vibrotactile Feedback Results

Fig. 2 also shows how well subjects used vibrotactile feedback. For both control methods, the mean 'proportional' vibrotactile feedback λ_c scores were higher than 'on-off' vibrotactile feedback scores (Welch's t-test, hand movement, $p = 0.013$; pinch force, $p = 0.042$). Additionally, subjects used pinch force control better than hand movement control during both types of vibrotactile feedback (Welch's t-test, 'proportional', $p = 1.10e-5$; 'on-off', $p = 3.51e-7$).

These results might not be surprising, given that pinch force control afforded better control even under visual feedback. However, if we normalize the vibrotactile feedback results by the average λ_C achieved during visual feedback, both vibrotactile feedback methods still generate better control when using pinch force rather than using hand movements (Welch's t-test, 'proportional', $p = 0.0037$; 'on-off', $p = 9.68e-4$). These results can be seen in TABLE I.

C. No Feedback Results

Finally, we show that all forms of feedback allow for better control than no feedback. "No feedback" means that we provided no feedback about the current state of the unstable system. However, subjects could still see their hand movements and feel their own pinch force. These results provide a baseline level of control when only the input to the system is known. It could be possible that subjects may take their input signal, run it through a mental

TABLE I – VIBROTACTILE CRITICAL INSTABILITY SCORES NORMALIZED BY VISUAL FEEDBACK SCORE

Control Method	Feedback Method (Normalized λ_C)	
	Proportional Vibrotactile	***On-Off Vibrotactile***
Hand Mvmt	0.41 ± 0.09	0.36 ± 0.09
Pinch Force	0.49 ± 0.16	0.43 ± 0.11

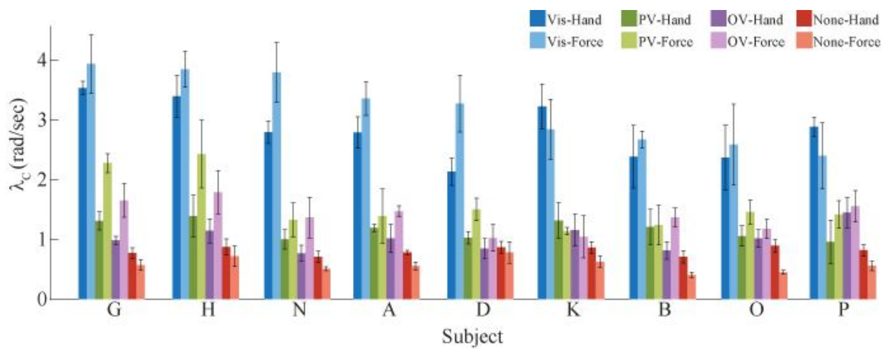

Figure 3 – CST λ_C results ordered by the subject's performance on visual feedback – force control. The feedback-control methods are: Vis – visual, PV – proportional vibrotactile, OV – on/off vibrotactile, None – no feedback.

simulation of the unstable system, and react appropriately. As we can see from these results, if such an internal model does occur, it does not work very well in this task.

D. *Intra-subject Variability*

Another finding is that there were striking differences between subjects in how well individuals could use a given type of control and feedback (Fig. 3). Under visual feedback, pinch force was the best strategy on average, however, subjects K and P were able to use hand control better than pinch force control. Additionally, subjects G and H were able to use pinch force with vibrotactile feedback very well. These discrepancies in subjects' optimal control and feedback methods highlights the potential need to customize the feedback rendering strategy for to the subject.

IV. Conclusion

We interact with the objects around us through arm and hand movements. Only recently are BCIs being developed that interact with objects. As a first step towards a BCI that can interact with the environment through non-visual feedback, we sought to develop a suitable experimental paradigm. Our Critical Stability Task is a novel paradigm that bears some similarities to the control of grasp, in that the feedback depends on the interaction between the object and the user's actions, and that feedback is not necessarily visual. We investigated different vibrotactile feedback methods, and also different input methods. We found that the optimal input and feedback type differed somewhat between subjects. In this way, our approach provides a blueprint for the customization of tasks and feedback type for different applications, eventually including BCI control under non-visual feedback.

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