Feedback Delay Changes the Control of an Inverted Pendulum

Sae Franklin, Justinas Česonis, Raz Leib, and David W. Franklin, *Member, IEEE,*

Abstract— **We recently developed a simulated inverted pendulum in order to examine human sensorimotor control strategies for stabilization. This simulated system allows us to manipulate the visual and haptic feedback independently from the physical dynamics of the task. Here we examine the effect of sensory delay in a balancing task. Human participants attempted to balance an inverted pendulum (simulated on a robotic manipulandum) with three different added delays (25, 50, and 75 ms), where the same delay was added to both the visual and haptic feedback. Increasing sensory delays decreased the ability of the participants to stabilize the pendulum. Investigation into the online control of the pendulum showed that with longer delays participants reduced their movement frequency but increased the amplitudes of their corrections.**

I. INTRODUCTION

Humans have an exceptional ability to control novel tools and complex systems despite the presence of noise and delays in their sensorimotor control system that increase their uncertainty in the state of the external world [1]. One way in which this compensation occurs is through the development of predictive forward models that can be used to predict the current and future state of our body [2] and the external world [3, 4]. However, the external world is not always predictable. Control also arises through the modification of task-dependent feedback responses. For example, it has been shown that visuomotor feedback control exhibits task-dependent modulation [5, 6], that is adjusted to increased uncertainty in our predictive model of the environment [7].

Adaptation or upregulation of task-dependent feedback control depends on the access to reliable sensory information. When the uncertainty in this sensory feedback increases, the movement times increase [8] or the movement trajectories are modified [9] in order to improve the reliability of sensory information. Unlike simple reaching movements where the future is often easy to predict even in the absence of accurate sensory information, the real world contains unstable situations, in which the future is no longer predictable. In unstable environments we find upregulation of muscle stiffness and feedback control [10]. However, in the control of complex external objects co-contraction may not always work.

Increased uncertainty in the external world can occur through a variety of methods. Here we assess the effect of increasing feedback delay during the control of an unstable inverted pendulum in order to study the changes in the control system under such complex interactions. Building on prior work in human sensorimotor control investigating the control of an inverted pendulum [11, 12], we previously developed a simulated inverted pendulum [13, 14] on a robotic manipulandum, that allows us to control the specific visual and haptic feedback provided to the participants. Our previous work showed how incongruent feedback affects the control and stabilization of unstable dynamics. There we showed that fixating visually to the center of mass of the pendulum allowed for the best control while visual feedback at a location away from this point decreases the performance [13, 14]. Here we further investigate the effect of feedback on stabilization by introducing delay between the action participants used to stabilize the pendulum and the sensory feedback they received. Such manipulation allows us to examine how the human sensorimotor control strategies change in order to stabilize the inverted pendulum.

II. MATERIALS AND METHODS

A. Participants

Six neurologically healthy, right-handed [15] human participants (3 female) took part in the experiment (aged 28.1 ± 3.4, mean ± SD). Participants were naïve to the study purpose and provided written informed consent before participation. The study was approved by the institutional ethics committee at the Technical University of Munich. All participants provided written informed consent prior to participating in this experiment.

B. Experimental apparatus

Participants were required to balance an inverted pendulum simulated on a planar robotic manipulandum (Fig. 1). Participants were seated with their right arm resting on an airsled and their right hand grasping the handle of the vBOT robotic interface [16]. Position and force data were sampled at 1 kHz. Visual feedback was projected veridically via a computer monitor and a mirror system to the plane of the movement such that direct visual feedback of the hand was prevented.

C. Experimental protocol

The inverted pendulum was simulated in the x-y plane with the gravity acting in the negative y direction while corrective movements were performed in the x-axis. Mechanically the pendulum was represented as a point mass (m = 1 kg) balanced at height (L) above a cart (M = 0.1 kg). The dynamics equations of the pendulum and general details of the inverted pendulum system and the visual feedback to the participants are outlined in our previous papers [13, 14].

The cart, controlled by the participant, was represented visually as a 1.5 cm by 3.0 cm red block. It was constrained

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S. Franklin is with the Institute of Cognitive Systems, Department of Electrical and Computer Engineering, Technical University of Munich, Munich, 80333 Germany (e-mail: sae.franklin@tum.de).

J. Česonis, R. Leib and D.W. Franklin are with Neuromuscular Diagnostics, Department of Sport and Health Sciences, Technical University of Munich, Munich, 80992 Germany (phone: +49 89289 24536; e-mail: justinas.cesonis@tum.de, raz.leib@tum.de, david.franklin@tum.de).

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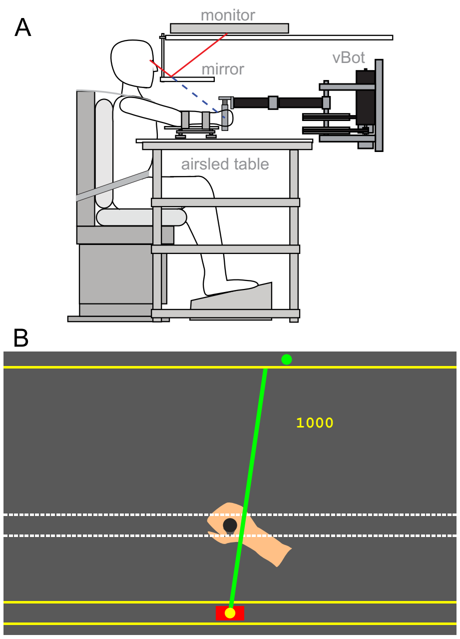

Figure 1. Experimental design. **A**. Participants were seated with their forearm resting on an airsled and grasped the handle of a robotic manipulandum. Visual feedback was provided in the plane of movement via a mirror and monitor system. **B**. Sample of the visual feedback provided to participants. The circular cursor at the top of the screeen provides visual feedback of the tip of the pendulum while the pendulum is truncated at the top of the screen due to size constraints. The y-coordinate of the physical hand location (not visible to participants) was offset from the hand position and shown here for illustrative purposes only. Participants controlled the position of a cart (red square) with their hand and attempted to balance a virtual inverted pendulum (green line).

to a single axis of motion in the x direction approximately 30 cm in front of participant's chest by a simulated mechanical channel (stiffness 4000 N/m; damping 2 Ns/m; maximum force value of 25 N). This channel was framed visually on the screen by two yellow lines of 1.0 mm thickness. Any force F_x exerted by the pendulum on the cart was applied on the handle in the x direction. For safety reasons this force was saturated at the absolute value of 5 N and switched off completely when the pendulum angle exceeded 30° from the vertical (past point of recovery). The actual physical hand location was shifted 13.0 cm in a positive y- direction while the x-coordinate of the cart and the handle matched throughout the experiment in order to maximize the movement range of the participants. The pendulum was represented as a green line of 3.0 mm thickness connected to the center point of the cart. Due to the limitations of the screen size the pendulum was truncated at the top of the screen. In addition, a green circle (d = 1.0 cm) moving only in x direction was presented at the top of the screen. This circle represented the lateral motion of the visual feedback point of the pendulum, which was also the location of the simulated center of mass of the pendulum.

Trials were self-paced: participants initiated each trial by moving the cart to the start position, indicated by a grey rectangle (3.0 cm by 1.5 cm). Participants were notified that they were within the home position by a yellow circle (d = 1.0 cm) appearing at the center of the cart. The start of the trial was notified by a short beep. This was followed 600 ms later with the pendulum starting to fall with an initial angular velocity of ± 0.01 rad/s and fall direction randomized with equal probabilities for left and right. Participants were instructed to maintain the pendulum in an upright position and with as little oscillation as possible. A trial was considered to have terminated when the angle between the pendulum and the y-axis reached 90º or when the pendulum was successfully balanced for 5.0 s. Participants were then free to return to the start position and initiate the next trial while the feedback about the previous trial was shown. To provide comparable feedback for the participants a score [13] was provided at the end of each trial which depended on the length of time balanced and how upright the pendulum was maintained.

First, all participants practiced controlling the pendulum for 96 trials with six different lengths L = [0.5 m, 0.75 m, 1 m, 1.5 m, 2 m, 4 m], in the familiarization session with no added visual feedback delay. Then after this familiarization session, participants started the main experiment with 540 trials in 18 blocks (30 trials in each block) per participant. Between blocks a short break was provided (3 s). This main session consisted of three experimental conditions – three different feedback delays of 25 ms, 50 ms and 75 ms. These conditions were blocked, with the order counterbalanced across participants. For each feedback delay condition, participants attempted to balance pendulums of six different lengths L = [0.5 m, 0.75 m, 1 m, 1.5 m, 2 m, 4 m]. Each block (30 trials) contained trials using the same length of pendulum. The visual feedback location (circle at top of screen) was also provided at this length such that participants could always see the lateral motion of the center of mass of the pendulum. However, the visual and haptic feedback was always provided at a delay to participants. That is, although participants could affect the motion of the pendulum immediately through movement of the cart, they only received delayed feedback (visual and haptic) with a delay of 25, 50 or 75 ms.

D. Analysis

Data was analyzed offline using MATLAB R2018a. Force and kinematic data were low-pass filtered using a fifth order, zero-phase-lag Butterworth filter (40 Hz cutoff). Data was then combined across participants. Error bars indicate standard error of the mean. For the frequency and amplitude analysis, only the trials in which the participants were successful in stabilizing the pendulum were used.

III. RESULTS

Six participants each performed one session in which they were requested to balance a simulated inverted pendulum. During this session we investigated the effect of delayed feedback on control of the inverted pendulum by adding different delay values between the participants action and the sensory feedback of the consequences of their action in order to observe how inaccurate or uncertain estimates impact the controllability of an unstable system.

As this feedback delay increased, participants achieved lower scores across all lengths of the pendulum (Fig. 2A). This effect is partially explained by the decrease in the time for which the pendulum could be maintained upright (Fig. 2B). However, even at the longest lengths (2 m and 4 m)

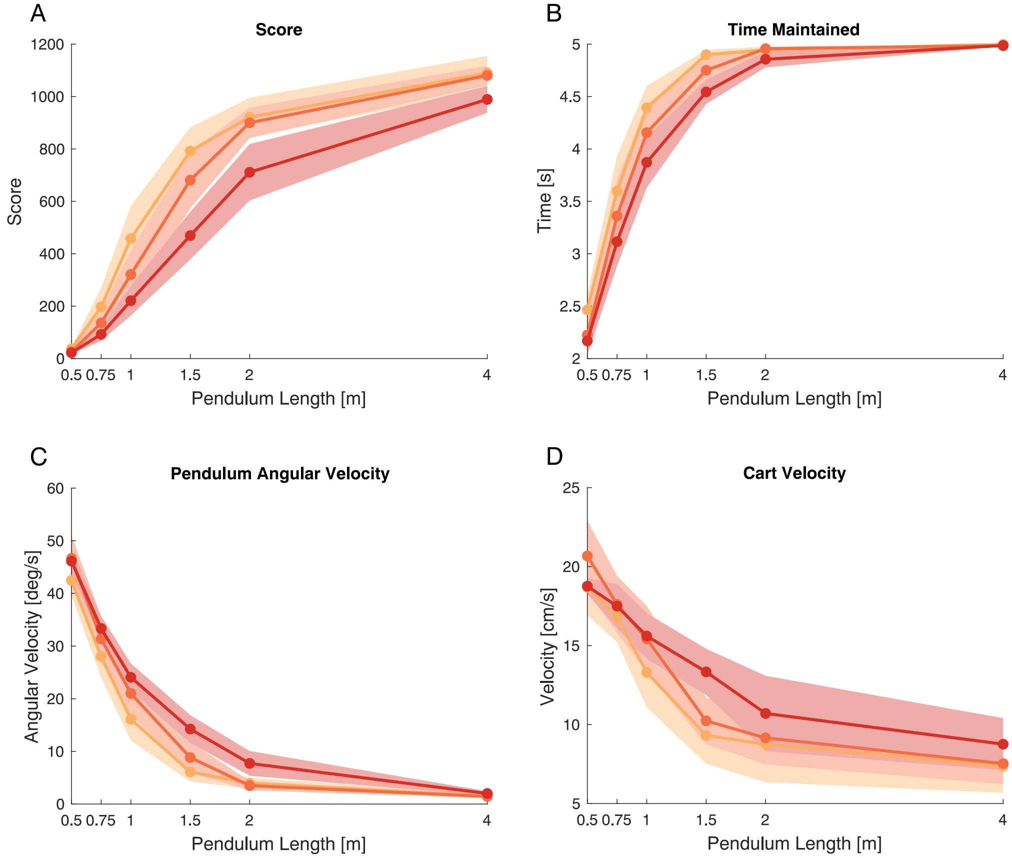

Figure 2. Effect of pendulum length and feedback delay on the controlability of the inverted pendulum. Mean data across participants is shown for feedback delays of 25ms (light orange traces), 50 ms (dark orange traces) and 75 ms (red traces) as a function of the pendulum length. **A.** Score. Solid lines indicate mean responses across participants. Shaded areas represent the standard error of the mean. **B**. Time that the pendulum was maintained upright for each condition. Individual trials were capped at 5s. **C**. Mean pendulum angular velcocity. **D**. Mean velocity of the handle (cart). The cart velocity represents the control actions issued by the participants.

where the time maintained upright was consistent across all delay conditions the score was lower. This can be explained by the increases in the angular pendulum velocity and cart velocity (Fig. 2, C&D). In particular, it appears that participants increased the motion of the cart and therefore the pendulum as the delay increased.

In order to get further insight into the changes in the control strategy of the delayed inverted pendulum, the frequency and amplitude of the cart motion and pendulum angle was calculated for all successfully maintained trials (Fig. 3). As the feedback delay increased, the peak frequency of participants motions of the cart decreased (Fig. 3A) but the amplitude of these corrective movements increased (Fig. 3B). Thus, it appears that participants deal with the increased feedback delay by decreasing the frequency of their corrective actions resulting in increased amplitude of these corrections when they occur. As expected this produces similar changes the frequency and amplitude of the variations in pendulum angle (Fig. 3, C&D). Therefore, with increased delay participants reduce the frequency of their corrective actions but therefore allow larger motions of the pendulum.

IV. DISCUSSION

We investigated the introduction of sensory feedback delays into the control of an inverted pendulum by human participants. As the delay in this feedback was increased, participants had more difficulty in balancing the pendulum and for shorter pendulum lengths this resulted in fewer trials that could be maintained for the full length of each trial. However, even at the longest pendulum lengths, where participants were able to keep the pendulum upright for the full trial, the scores were lower overall (Fig. 2A). Analysis of the control behavior showed that as the delay increased participants reduced the frequency but increased the amplitude of their control.

Our results are consistent with previous findings of lower movement frequency together with motion hypermetria when visual feedback is delayed. This is evident in a variety of motor tasks where delay was introduced between the movement and the visual feedback, for example, during target tracking [17-19], object interception [20], or reaching movements [21]. One possible explanation for movement hypermetria suggests that the motor system does not explicitly represent time delay but instead uses state variables to approximate delay. Using this approximation, the internal representation of the controlled object's dynamics is modified and, as a result, so too are the movements that are generated for control [17, 20]. The results of our study extend these findings of increased frequency and hypermetria to a complex task in which participants were required to control an unstable object.

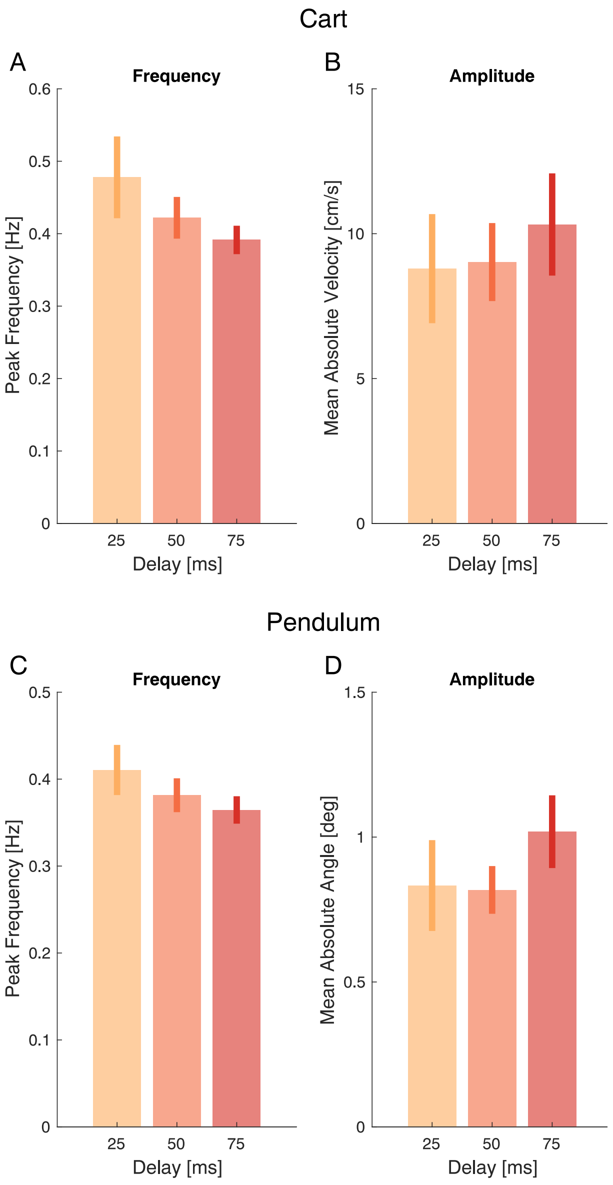

Figure 3. Frequency analysis of the control. The top plots examine the frequency and amplitude of the cart control, whereas the bottom plots examine the effect of the frequency and amplitude of the pendulum angle. **A**. The mean peak frequency of cart velocity for the three control delays across all participants. Only successfully balanced trials were included in the analysis. Error bars represent SEM across the participants. **B**. The mean absolute cart velocity. **C**. Mean peak frequency of the pendulum angle. **D**. Mean absolute pendulum angle.

In order to balance an inverted pendulum, the control system needs to estimate both the system inertia and the location of the center of mass with respect to the hand position. Through the introduction of a sensory delay, we expect to have increased the uncertainty in the participants estimates of both of these parameters and thereby influenced the used control strategy. This increased uncertainty slowed the frequency of the control. This difference could manifest itself in a shift of the gain from rapid visuomotor feedback responses [22] to slower voluntary corrections. Our future work will examine this possibility by combining our visual perturbations with the control of the inverted pendulum.

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