Influence of Visual Feedback on the Sensorimotor Control of an Inverted Pendulum

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

***Abstract*— We examine the visual influence of stabilization in human sensorimotor control using a simulated inverted pendulum. As the inverted pendulum is fully simulated, we are able to manipulate the visual feedback independently from the dynamics during the motor control task. Human subjects performed a balancing task of an upright pendulum on a robotic manipulandum in two different visual feedback conditions. First we examined how subjects perform a task where the visual feedback is congruent with the pendulum dynamics. Second we tested how subjects performed when the physical dynamics were fixed but the visual feedback of the pendulum length was modulated. Subjects exhibited deficits in the control of the pendulum when haptic and visual feedback did not match, even when the visual feedback provided more sensitive information about the state of the pendulum. Overall we demonstrate the importance of accurate feedback regarding task dynamics for stabilization.**

I. Introduction

Motor adaptation to novel dynamics occurs rapidly using sensory prediction errors to update the current motor memory. This suggests that access to reliable feedback is critical to the motor adaptation process. This adaptation is strongly driven by proprioceptive input [1], [2], although studies have also shown the importance of visual feedback [3]. Here we assess the effect of accurate feedback during learning to stabilize a simulated inverted pendulum. Through simulation of the inverted pendulum on a robotic manipulandum, we can control the specific visual and haptic feedback provided to the participants, where these two sensory modalities can provide congruent or incongruent feedback about the movement.

The use of an inverted pendulum to study human motor control [4]-[7] is similar to the use of other unstable tasks such as divergent force fields [8]-[10], spring compression [11] or object interaction [12], [13]. In order to maintain control of the system and prevent failure, the control strategy requires either co-contraction to increase the stiffness [14] or high feedback gains [6], [15] to correct small deviations away from the desired location. Here we simulate the balancing of an inverted pendulum, controlled by the lateral motion of a cart that can be controlled by the participant. As the connection between the cart and the pendulum is un-actuated, subjects cannot stiffen this joint and therefore must rely on feedback control of the pendulum angle in order to maintain the upright posture. In this study we examine the control of the task in two different experiments. In experiment 1, pendulum length was varied and visual feedback was provided at the location of the center of mass. In experiment 2, the pendulum length remained constant, but visual feedback was provided at a range of locations along the pendulum (both above and below the center of mass The goal of this study is to examine how incongruent feedback affects the control and stabilization of unstable dynamics.

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 and D.W. Franklin are with Neuromuscular Diagnostics, Department of Sports and Health Science, Technical University of Munich, Munich, 80992 Germany (phone: +49 89289 24536; e-mail: justinas.cesonis@tum.de, david.franklin@tum.de).

II. Materials and Methods

A. Subjects

Six neurologically healthy, right-handed [16] human subjects (1 female) participated in both experiments (mean age 29.0 years). Subjects 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.

B. Experimental apparatus

Participants were required to balance an upright pendulum simulated with a planar robotic manipulandum. Participants were seated with their right arm resting on an airsled and their right hand grasping the handle of the vBOT robotic interface [17]. A six-axis force transducer (ATI Nano 25; ATI Industrial Automation) measured the end-point forces applied on the robotic handle by the participant. The handle position in the workspace was calculated from joint-position sensors (58SA; Industrial Encoders Direct) on the motor axes. 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 paradigm

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 dynamic equations of motion describing the system are:

$$F_x = \ddot{x}(m \sin^2\theta + M) - mL\dot{\theta}^2 \sin\theta + mg\sin\theta\cos\theta \quad (1)$$

$$\ddot{\theta} = (g\sin\theta - \ddot{x}\cos\theta)/L \quad (2)$$

where F_x is the lateral force applied by a pendulum on the cart, θ is the angle between the pendulum and the y-axis, x is the position of the cart and g is the gravitational acceleration constant.

The cart, controlled by the subject, was represented as a 1.5 cm by 3.0 cm red block. It was constrained 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 and 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 (not experienced during the experiments) 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 subjects. The pendulum was represented as a blue 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 blue 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 depended on an experimental condition.

Trials were self-paced: subjects 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 trial initiation cue was a short beep followed by the pendulum starting to fall after 600 ms with initial angular velocity $\dot{\theta} = 0.01$ rad/s where the fall direction was randomized with equal probabilities for left and right. Subjects were required 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 90^o or when the pendulum was successfully balanced for 5.0 s. Subjects 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 consistent feedback for participants a score variable (S) was introduced:

$$S = 100 \ln\left(\frac{9000}{\sum_{t=0.001}^{5} \theta(t)^2}\right) \quad (3)$$

where t is time sampled at 1000 Hz for the duration of the trial. If the pendulum was not maintained upright for the duration of the trial, $\theta = 90^o$ was used for all the remaining samples until the end of the trial.

Participants completed two experimental conditions. In the first condition participants were asked to balance pendulums of different lengths L = [0.25 m, 0.5 m, 0.75 m, 1 m, 1.5 m, 2 m, 4 m, 6 m, 8 m]. For each length, the visual feedback location was also provided at this length such that participants were always looking at the lateral motion of the center of mass of the pendulum (Fig. 1C). Each experimental block consisted of 20 trials of one given pendulum length. The nine different blocks were presented twice to participants in a pseudo-random order, so that every pendulum length was presented before any of the lengths was repeated. Between blocks a short break was provided (3 s). This resulted in 40 repetitions of each pendulum length and a total of 360 trials per participant.

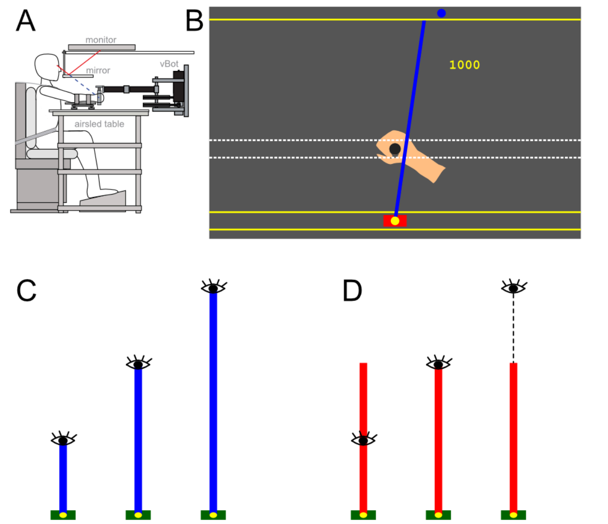

Figure 1. Experimental design. **A**, Subjects performed the stabilization task using a planar robotic manipullandum. Visual and haptic feedback were provided in the plane of movement. **B**, A sample snapshot of an experimental trial. The circular cursor at the top of the screen provides visual feedback of the point of interest while the pendulum is truncated at the top of the screen due to the size constraints. The y-coordinate of the physical hand location (not visible to subjects) is offset with respect to the cart position due to the physical limitations of the robotic system. **C**, In experimental condition 1 the mechanical lengths of the pendulum were varied and visual feedback of the centre of mass was provided for each virtual pendulum. **D**, In experimental condition 2 the mechanical length for each pendulum was constant while the location of the visual feedback was varied for different trial blocks (below, concurrent or above the center of mass).

In the second experimental condition, a pendulum with dynamic properties according to a pendulum of length L = 2 m was presented to participants in all trials. However, the visual feedback location was provided to participants at lengths L_v = [0.25 m, 0.5 m, 0.75 m, 1 m, 1.5 m, 2 m, 4 m, 6 m, 8 m] in a pseudo-randomized blocked fashion similar to the experimental condition 1 (Fig. 1D). Each participant performed a total of 360 trials.

III. Results

The distances between the cart and visual feedback location were matched across lengths between both experiments. However, in experiment 1 changes in length also produced changes in dynamic behaviour, whereas in experiment 2 the dynamics remained constant while visual feedback varied. This separates the effects of visual and proprioceptive feedback in the pendulum control and allows us to observe how varying the one or both modalities impacts control strategy and controllability of a pendulum.

One condition (L = 2 m) matched across both experiments in terms of dynamics and feedback. As expected, the performance at these conditions did not differ between experiments (Fig. 2, 3). Increasing the length of the pendulum had different consequences for the two experiments. In experiment 1 participants maintained or slightly improved their performance compared to L = 2 m (Fig. 2A, B). This is an expected result as longer pendulums are inherently more stable than the short ones. In experiment 2, participants struggled to control the pendulum when visual feedback location was moved above the center of mass (Fig. 2A, B) and produced much larger corrective response (Fig. 2C). In these conditions the pendulum behavior was less stable compared to the matching visual feedback, as represented by angular velocity (Fig. 3A). Note that seemingly small decrease in the balance duration (Fig. 2B) compared to L = 2 m for experiment 2 may be much larger, as all trials were terminated at t = 5 s.

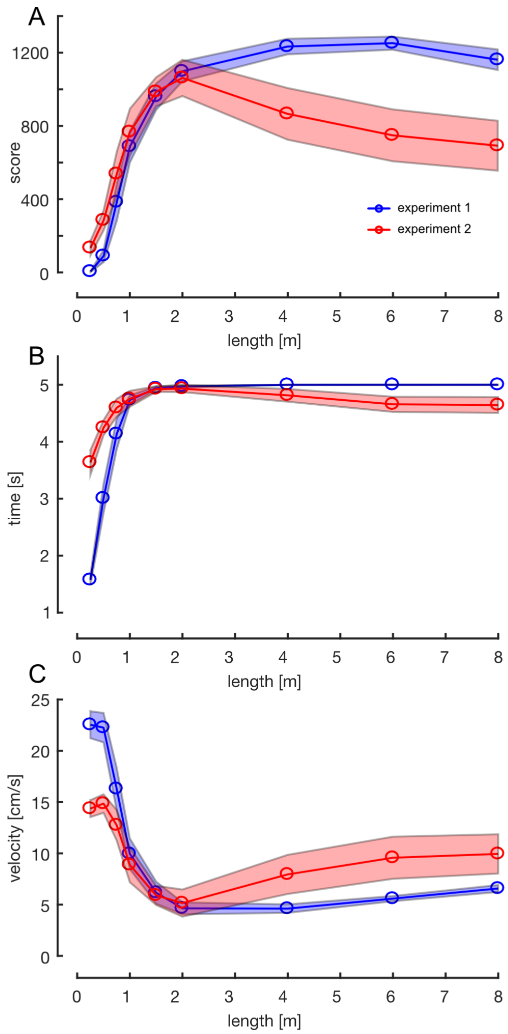

Figure 2. Effect of pendulum length and visual feedback length on the controlability of the inverted pendulum. Results are shown for both experiment 1 (blue) and experiment 2 (red). **A**, Score. Solid lines represent mean responses between the individual subjects. Shaded areas represent standard error of the mean (SEM). Note that for experiment 2, the results are plotted as a fucntion of the visual feedback length. **B**, Time that the pendulum was maintained upright for each condition. Individual trials were capped at 5 seconds, explaining consistent durations for the long lengths of the pendulum. **C**, Average velocity of the handle (cart) for each length of the pendulum. Cart velocity represents control actions issued by subjects.

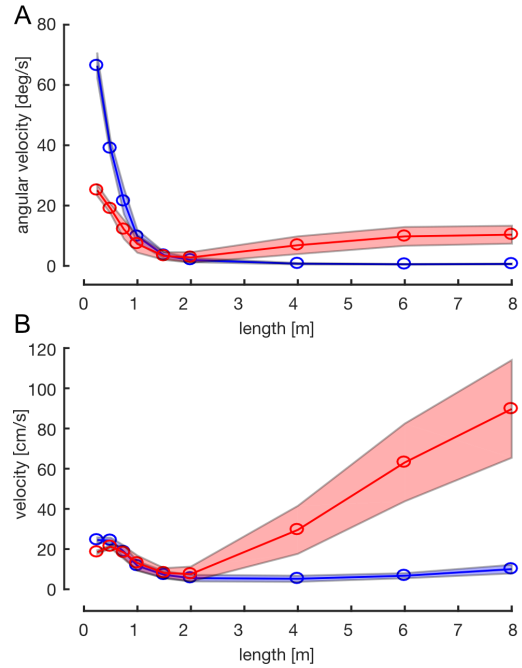

Figure 3. Comparison of the angular velocity and visual feedback velocity for varying pendulum length (blue) and varying visual feedback location (red). **A**, Angular velocity of the pendulum variation with test length for both experimental conditions. Angular velocity represents the total instability in the system and is invariant of the test condition. Solid lines represent mean responses between the individual subjects. Shaded areas represent standard error of the mean (SEM). For both experimental conditions the visual feedback was matching at the % original length values, while the dynamic length was different. The behavior and feedback at 100% original length is identical for both experimental conditions. **B**, Average velocity of the feedback point for each test condition.

For very short physical lengths (L ≤ 0.5 m) the pendulum was uncontrollable based on both the maintained time and score (Fig. 2A, B), although the control input by participants was significantly larger than for other lengths (Fig 2C). This is expected, as the time constant (τ_p < 0.23 s) of the pendulum is comparable to visual time delay (dead-time) $\tau \approx$ 0.15 s. The pendulum becomes somewhat controllable at L = 1 m, $\tau_p = 0.32$ s $\approx 2\tau$ consistent with Ziegler-Nichols tuning rules for a derivative controller. Experiment 2 shows the reliance on visual feedback for control, as even though the dynamics match a 2 m pendulum, we observed a deficit in performance as the viewing length decreased.

IV. DISCUSSION

Our results show the effect of different visual feedback locations or gains in controlling an inverted pendulum. More specifically, we show that fixating visually to the center of mass of the pendulum allows for the best balance while visual feedback at a location away from this point decreases the performance. While visual feedback at shorter lengths could be expected to decrease performance due to sensory noise and perceptual thresholds (a larger error is required to signal a corrective response), such an interpretation could not explain the decrement with longer viewing lengths. However the accuracy of the estimate of both the system inertia and the location of the center of mass with respect to the hand position are critical to balance the system.

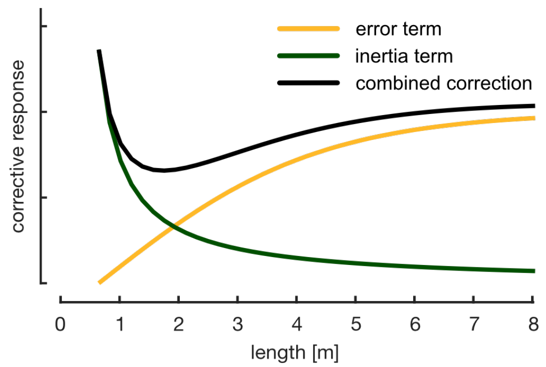

Figure 4. Theoretical corrective response model. Humans have non-linear behaviour when correcting for errors. The corrective response increases approximately linearly for small errors until it saturates for larger errors (yellow). On the other hand, the perceived inertia of the system varies invesely. Subjects would estimate inertia based on the visual motion according to their applied force (m=F/a). However, acceleration of the viewpoint varies linearly with pendulum length (effective visual gain), making the perceived inertia inversely proportional to visual length (green). The total corrective response (black) matches the red curve in Fig 2C and is minimised at the point where visual length matches the dynamics and is dominated by one of the two mechanisms as this length changes.

Direct visual representation of the motion of the center of mass allows for the optimal estimation of the two variables. As viewpoint is moved away from this location, both of these inputs have to be estimated to determine the appropriate control action. For a viewpoint above the center of mass a perceived error may be overestimated producing an over reactive response, as the same angular error now results in a larger lateral deviation (Fig. 4). On the other hand, these viewpoints above the center of mass also respond faster to control inputs, making the system look like it has less inertia than it has. This could produce under-compensation in a corrective response, as the system appears more responsive. The opposite is true for both behaviors when the viewpoint is moved to a length shorter than the center of mass. However, it has been shown that human response to errors is not linear with respect to the error size, but the perceived inertia of the system is inversely proportional to the distance of a viewpoint. Thus for different visual locations one of these two effects will dominate the response, making it more likely to produce an inappropriate corrective response. The combination of these two mechanisms allows the best performance to be achieved when visual feedback matches the dynamics of the system while degrading it when moving away from this point.

These results demonstrate that tuning of the feedback gains appropriately for the task dynamics is critical to achieving optimal performance. Several studies have shown that such visuomotor feedback gains can be tuned appropriately for both visual and physical environments [18], [19]. Thus we expect that given sufficient training with both the pendulum and the modified visual feedback subjects could learn to improve performance in the incongruent visual feedback conditions. These results demonstrate that it is important to understand the manner in which the sensorimotor control system learns and tunes the feedback responses to the external environment. In this paper we have shown the effect of manipulating the visual feedback on the control of a simulated inverted pendulum. However we believe that the largest impact is demonstrating the potential applications of this simulated control task for studying sensorimotor control. Through selective modification and perturbation of the visual and haptic feedback we will study how humans process, respond and adapt to these inputs to control unstable tasks, and gain insight into the computations of sensorimotor control.

References

[1] P. DiZio and J. R. Lackner, "Congenitally blind individuals rapidly adapt to coriolis force perturbations of their reaching movements.," *J Neurophysiol*, vol. 84, no. 4, pp. 2175–2180, Oct. 2000.

[2] D. W. Franklin, U. So, E. Burdet, and M. Kawato, "Visual feedback is not necessary for the learning of novel dynamics.," *PLoS ONE*, vol. 2, no. 12, p. e1336, 2007.

[3] F. R. Sarlegna, N. Malfait, L. Bringoux, C. Bourdin, and J.-L. Vercher, "Force-field adaptation without proprioception: can vision be used to model limb dynamics?," *Neuropsychologia*, vol. 48, no. 1, pp. 60–67, Jan. 2010.

[4] B. Mehta and S. Schaal, "Forward models in visuomotor control.," *J Neurophysiol*, vol. 88, no. 2, pp. 942–953, Aug. 2002.

[5] I. D. Loram and M. Lakie, "Human balancing of an inverted pendulum: position control by small, ballistic-like, throw and catch movements.," *J. Physiol. (Lond.)*, vol. 540, no. 3, pp. 1111–1124, May 2002.

[6] I. D. Loram, H. Gollee, M. Lakie, and P. J. Gawthrop, "Human control of an inverted pendulum: Is continuous control necessary? Is intermittent control effective? Is intermittent control physiological?," *J. Physiol. (Lond.)*, vol. 589, no. 2, pp. 307–324, Jan. 2011.

[7] J. L. Cabrera and J. G. Milton, "Human stick balancing: tuning Lèvy flights to improve balance control.," *Chaos*, vol. 14, no. 3, pp. 691–698, Sep. 2004.

[8] D. W. Franklin, G. Liaw, T. E. Milner, R. Osu, E. Burdet, and M. Kawato, "Endpoint stiffness of the arm is directionally tuned to instability in the environment.," *J. Neurosci.*, vol. 27, no. 29, pp. 7705–7716, Jul. 2007.

[9] E. Burdet, R. Osu, D. Franklin, T. Milner, and M. Kawato, "The central nervous system stabilizes unstable dynamics by learning optimal impedance," *Nature*, vol. 414, no. 6862, pp. 446–449, 2001.

[10] D. W. Franklin, U. So, M. Kawato, and T. E. Milner, "Impedance control balances stability with metabolically costly muscle activation.," *J Neurophysiol*, vol. 92, no. 5, pp. 3097–3105, Nov. 2004.

[11] M. Venkadesan, J. Guckenheimer, and F. J. Valero-Cuevas, "Manipulating the edge of instability," *J Biomech*, vol. 40, no. 8, pp. 1653–1661, Jan. 2007.

[12] L. P. J. Selen, D. W. Franklin, and D. M. Wolpert, "Impedance control reduces instability that arises from motor noise.," *J. Neurosci.*, vol. 29, no. 40, pp. 12606–12616, Oct. 2009.

[13] D. W. Franklin, L. P. J. Selen, S. Franklin, and D. M. Wolpert, "Selection and control of limb posture for stability.," *Conf Proc IEEE Eng Med Biol Soc*, vol. 2013, pp. 5626–5629, 2013.

[14] D. W. Franklin, R. Osu, E. Burdet, M. Kawato, and T. E. Milner, "Adaptation to stable and unstable dynamics achieved by combined impedance control and inverse dynamics model.," *J Neurophysiol*, vol. 90, no. 5, pp. 3270–3282, Nov. 2003.

[15] S. Franklin, D. M. Wolpert, and D. W. Franklin, "Visuomotor feedback gains upregulate during the learning of novel dynamics.," *J Neurophysiol*, vol. 108, no. 2, pp. 467–478, Jul. 2012.

[16] R. C. Oldfield, "The assessment and analysis of handedness: the Edinburgh inventory.," *Neuropsychologia*, vol. 9, no. 1, pp. 97–113, Mar. 1971.

[17] I. S. Howard, J. N. Ingram, and D. M. Wolpert, "A modular planar robotic manipulandum with end-point torque control.," *J. Neurosci. Methods*, vol. 181, no. 2, pp. 199–211, Jul. 2009.

[18] D. W. Franklin, S. Franklin, and D. M. Wolpert, "Fractionation of the visuomotor feedback response to directions of movement and perturbation," *J Neurophysiol*, vol. 112, no. 9, pp. 2218–2233, 2014.

[19] S. Franklin, D. M. Wolpert, and D. W. Franklin, "Rapid visuomotor feedback gains are tuned to the task dynamics.," *J Neurophysiol*, vol. 118, no. 5, pp. 2711–2726, Nov. 2017.