A Technique for Measuring Visuomotor Feedback Contributions to the Control of an Inverted Pendulum

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***Abstract*— We developed a new technique to measure the contributions of rapid visuomotor feedback responses to the stabilization of a simulated inverted pendulum. Human participants balanced an inverted pendulum simulated on a robotic manipulandum. At a random time during the balancing task, the visual representation of the tip of the pendulum was shifted by a small displacement to the left or right while the motor response was measured. This response was either the exerted force against a fixation position, or the motion to re-stabilize the pendulum in the free condition. Our results demonstrate that rapid involuntary visuomotor feedback responses contribute to the stabilization of the pendulum.**

I. Introduction

Extensive studies have examined the mechanisms underlying human sensorimotor control. While much has focused on the predictive control of forces to adapt to changes in the loading during reaching, only a few studies have investigated the control involved in stabilizing unstable systems. A range of designs have been investigated including adaptation to divergent force fields [1], object interaction [2], spring compression [3], and stabilizing inverted pendulums [4]. Compensation for the instability has either been found to be increased co-contraction tuned to the instability [5], tuning of feedback responses [6] or both [1, 7]. The relative contribution of co-contraction or feedback control appears to depend on the falling time constant [8]. Extending previous work [6, 9-12], we have recently developed a simulated inverted pendulum implemented on a robotic system in order to investigate the human sensorimotor control system [13, 14]. While we have shown that the control of this pendulum is similar to the control of a physical pendulum [13], we have not yet shown the capability of the methodology to investigate other aspects of visuomotor control [15, 16].

Visuomotor responses have primarily been analyzed in reaching movements [16-20], where they exhibit a temporal evolution [21], such that they are not present when the hand is stationary [22]. Therefore, it is not clear whether these rapid visuomotor responses would contribute to the control of an inverted pendulum. Here we extend our previous work in reaching movements to develop a new technique to study the visuomotor feedback responses involved in stabilizing an inverted pendulum.

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II. Materials and Methods

A. Participants

Six neurologically healthy, right-handed human participants (2 females) participated in the experiment (mean age 36.6 years). Participants provided written informed consent before participation. The study was approved by the institutional ethics committee at the Technical University of Munich. All participants had previously experienced the simulated inverted pendulum during other experiments.

B. Experimental apparatus

Participants were asked 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 [23]. Position and force (ATI Nano 25) 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. 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 of 1 kg balanced at height 2.0 m above a cart with mass 0.1 kg. Participants were constrained to a single axis of motion in the x-axis by a simulated mechanical channel (stiffness 6000 N/m; damping 2 Ns/m). General details of the inverted pendulum system and the visual feedback to the participants are outlined in our previous papers [13, 14]. In the current experiment participants only received visual feedback of the pendulum and the lateral forces applied by the pendulum on the cart were zero in all conditions. Similar to our previous work, the pendulum was shown as a green line truncated at the top of the screen, where a green circle (d=1.0 cm) moving only in the x-axis represented the lateral motion of the top of the pendulum.

C. Experimental protocol

Participants were seated, grasping the handle of the robotic manipulandum. At the start of each trial, the participant's hand (represented visually by the cart) was moved by the robot to the starting position in the middle of the screen (laterally). Once the cart was stationary within the start location, a beep indicated the start of the trial, 600 ms after which the pendulum started to fall with an angular velocity of ± 0.01 rad/s. Participants were instructed to maintain the pendulum as vertically as possible with as little oscillation as possible. Each trial was terminated after 5 s or when the pendulum fell over (angle > 90.0º). After each trial, a score [13] was provided. Participants performed a total of 600 trials.

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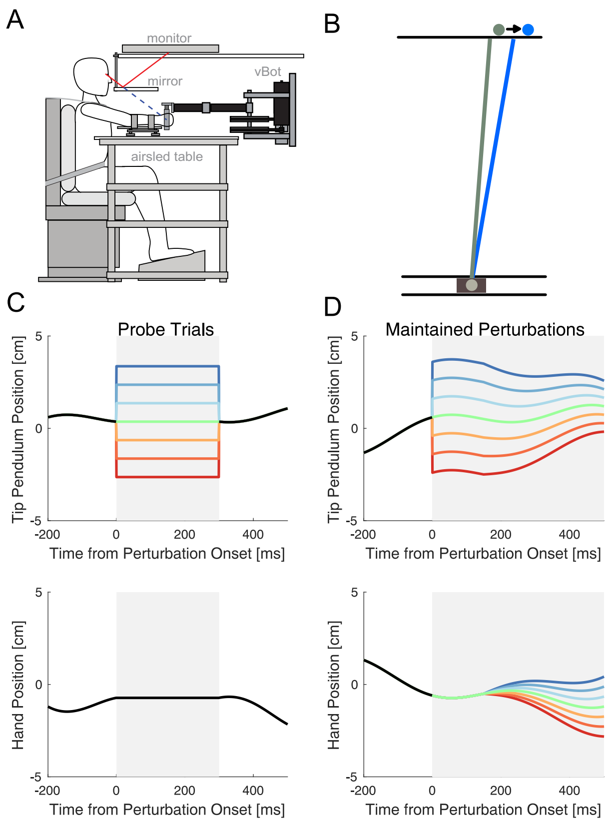

Figure 1. Experimental Design. **A**. Participants were seated with their forearm resting on an airsled while grasping the handle of a robotic manipulandum. Visual feedback was provided in the plane of movement via a mirror and monitor system. **B**. Participants controlled the position of a cart (grey box) with their hand and attempted to balance a virtual inverted pendulum (grey line). As the length of the pendulum exceeded the top of the screen, the tip of the pendulum was represented by a circle (grey circle). At a random time in the trial, the tip of the pendulum could be instantaneously displaced laterally (blue line and circle). **C**. Top, On probe trials the visual perturbation lasted 300 ms (grey shaded region). The perturbation of the pendulum could range in size (shown by colors) but was returned to the original pendulum location. Bottom, During the perturbation the hand location was fixed in place by the robotic manipulandum. **D.** Top, On maintained perturbation trials, the visual perturbation of the pendulum was applied, but this displacement remained for the rest of the trial and therefore had to be corrected. Bottom, The hand position was unconstrained throughout the trial. Participants could be expected to correct the sudden change in the pendulum angle with a corrective movement of the hand.

D. Visual perturbations

In order to measure the visuomotor feedback response, a visual perturbation of the top of the pendulum was introduced on random trials. This perturbation could be one of two types: a temporary probe trial or a maintained perturbation (Fig. 1, C&D). For each type of perturbation, nine amplitudes [-4, -3, -2, -1, 0, 1, 2, 3, 4] cm were used, making a total of eighteen perturbation types. However, only a small number of -4cm and +4cm perturbations were applied and therefore these were not analyzed.

Similar to our technique during reaching movements [16], the temporary visual probe trial lasted 300 ms during which the hand was constrained to remain in the fixed location (lateral stiffness 6000 N/m; damping 2 Ns/m). As soon as this fixation was applied, the tip of the pendulum (circle) was shifted laterally by one of the nine amplitudes. The line of the pendulum was also shifted by the appropriate angle to match the tip of the pendulum. Any force produced in response to this visual shift could then be measured against the fixation wall. At the end of the perturbation time, the visual representation of the pendulum was returned to the location prior to the perturbation and the physical fixation was removed allowing participants to continue to control the pendulum. Note that participants did not need to respond to these visual only perturbations (probe trials).

In contrast, during the maintained perturbation trials the same initial visual perturbation was applied (nine different amplitudes), but this perturbation affected the simulated perturbation angle and was maintained for the rest of the trial. In this case, participants had to compensate for these perturbations in order to maintain the pendulum upright. In reaching movements these maintained perturbations have been used to keep the responses to visual perturbations consistent across a long experimental session [15].

On any one trial, one of these eighteen perturbation types was applied at a random time during the trial. The time of perturbation onset was uniformly sampled between 1.0s and 3.0 s after the start of the trial. However, if at this time the hand velocity was above 0.03 m/s or the hand acceleration was above 0.5 m/s^2 then the perturbation onset was delayed until these values returned below the threshold limits.

E. Analysis

Data was analyzed offline using MATLAB R2018a and statistics with JASP. Force and kinematic data were low-pass filtered using a tenth order, zero-phase-lag Butterworth filter (40 Hz cutoff). In order to examine the visuomotor feedback responses the temporal data was aligned to perturbation onset and any offset was removed. For each trial, the offset was calculated depending on the measure of interest. The pendulum tip position used the value of the position 2 ms prior to the perturbation for the offset. The lateral force used the mean value of the lateral force from -80 to -10 ms relative to the visual perturbation for the offset. After the offset was removed the traces were averaged across all repetitions for each of the perturbation types for each participant. Data was then combined across participants where the error bars indicate standard error of the mean.

III. Results

Six participants performed one session each, lasting approximately 1.5 hours, which was composed of 600 trials in which the participant attempted to balance the pendulum for 5 s. In each trial a perturbation of the pendulum tip was applied which either lasted for the rest of the trial requiring compensation or was applied for 300 ms, during which the hand was clamped. As the length of the pendulum was 2 m, participants were able to stabilize the pendulum on almost all trials (mean ± std falls/600 trials = 6 ± 11), and generally achieved scores above 1000 (mean ± std score = 1145 ± 77).

The probe trials were introduced in order to measure any rapid motor response to the visual shift of the pendulum during active control. Data was aligned to the perturbation onset. On the probe trials, the tip of the pendulum was shifted laterally while the hand position was constrained to remain in the same posture for 300 ms using a rigid mechanical PD controller on the robotic manipulandum. Individual trials for one participant and perturbation type can be seen (Fig. 2).

This technique is similar in concept to the use of mechanical channel trials during a reaching movement to measure the visuomotor feedback [7, 15, 16, 24]. The visual perturbation was applied in either direction and with various magnitudes (Fig. 3A). The lateral force in response to the perturbations shows a clear response according to the size and direction of the visual perturbation (Fig. 3B). While the force response to the zero perturbation remains close to zero (green trace), the response to rightwards visual perturbations elicited strong force responses in the hand towards the right (blue traces) which would act to bring the hand back underneath he pendulum. Similarly, visual perturbations of the tip of the pendulum to the left elicited strong force responses in the hand towards the left (red traces).

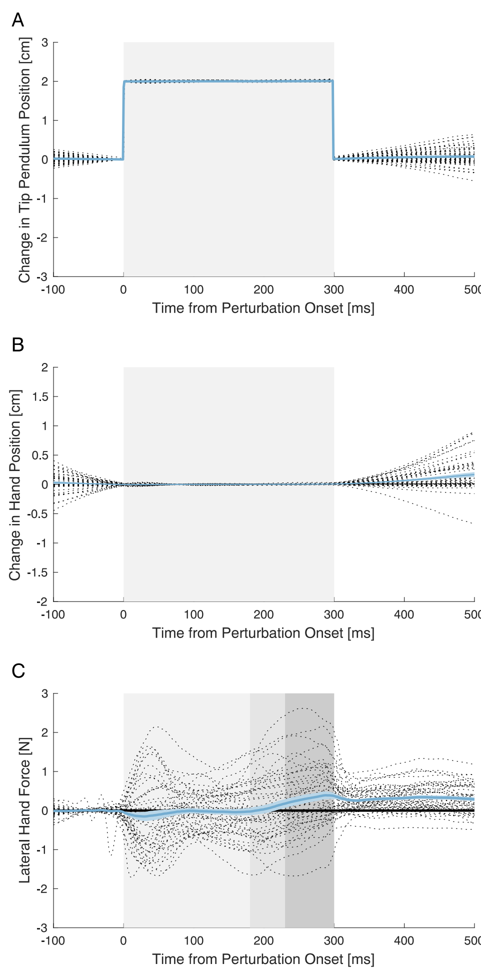

Figure 2. Visual perturbations of the pendulum tip during probe trials. Example data shown for all trials for one perturbation size (2.0 cm) for one exemplar participant. **A**. At a random time during the trial the tip of the pendulum was shifted laterally and held at this distance for 300 ms (shaded grey region). Individual trials shown by the dotted lines. Mean and SEM shown by the blue line and blue shaded region. **B**. During the perturbation, the participant's hand position was held constant by the robotic manipualdum. **C**. The lateral hand force exerted by the participant against the fixation channel. Due to the non-zero velocity prior to the fixation, initial force responses occur in both directions. In the later shaded regions, where a visuomotor feedback response would be expected to act, the mean force response shifts in the dirction of the visual perturbation.

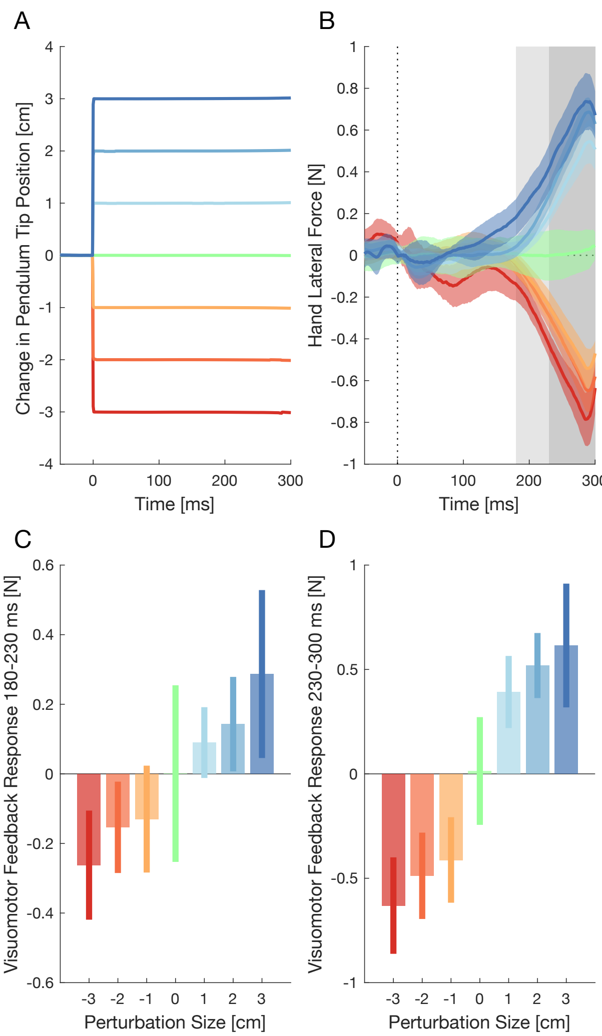

Figure 3. Visuomotor feedback responses during stabilization of an inverted pendulum. **A**. During inverted pendulum balancing, the tip of the pendulum undewent a rapid lateral shift. The color code illustrates the size of the shift from -3 cm (red) to +3 cm (blue). During this shift, the participant's hand was fixed in position by the robot so that any motor response could be measured against the fixation wall. **B**. The force responses at the hand after the visual perturbation of the pendulum tip was applied. Colors indicate the size of the perturbation. Mean (solid line) and sem (shaded region) across six participants. **C**. Mean visuomotor feedback response over the interval from 180-230 ms after the perturbation onset. Error bars indicate sem. **D**. Mean visuomotor feedback responses over the later interval (230-300 ms).

The force responses to the visual stimuli were then quantified over two intervals: 180-230 ms and 230-300 ms after the perturbation onset. The first interval has been used as an estimate of the involuntary feedback response as it has been shown to occur prior to any possible voluntary correction [16]. The second interval has been used to examine the visuomotor feedback tuning [17] as most of the power of the response occurs over this window. In the early interval (Fig. 3C) the force responses can be seen both in the appropriate direction, but also scaling with the size of the imposed perturbation ($F_{6,35}=7.104$; $p<0.001$). This demonstrates that the involuntary visuomotor feedback response contributes to balancing an inverted pendulum. This response scaling ($F_{6,35}$=32.47; p<0.001) is more clearly seen over the later window (Fig. 3D).

Importantly, while deceleration of the hand during the clamp can produce forces, on average the direction of these forces is independent of the direction of the visuomotor perturbation, allowing us to independently estimate the visuomotor response. This can be clearly seen on the zero visual perturbation condition where the position is clamped but the resulting forces are close to zero (Fig 3, green lines).

IV. Discussion

Here we demonstrated a new technique to examine the contributions of the visuomotor feedback system to the balancing of an inverted pendulum. In the middle of a trial the tip of the pendulum was shifted visually and the force response to this shift was measured against a rigid simulated channel. The presence of force responses in the involuntary time window demonstrate that rapid visuomotor feedback responses contribute to inverted pendulum balancing and may reflect the visual control of tools.

Previous studies have shown the presence of visuomotor feedback responses in reaching tasks, but not in primarily stationary tasks. In this study we have perturbed the pendulum in an effectively stationary state, however the responses were still present. Our results may suggest that the velocity of the movement is not directly responsible for the visuomotor feedback regulation. Alternatively, our results agree with previous research showing that urgency regulates these feedback gains [25, 26]. Although primarily stationary, our participants experienced the need to urgently correct for the perturbations. Therefore, our proposed methodology could be further used to investigate visuomotor feedback responses with uncoupled urgency and velocity.

This technique will allow us to investigate the feedback mechanisms involved in the control of more complex tools. Importantly we were able to demonstrate that these rapid involuntary visuomotor feedback responses exist during the control of an inverted pendulum. Moreover, these responses scaled according to the amplitude of the perturbation showing that they responded appropriately to the task. Our previous work has shown that these feedback responses can be tuned to either the visual task demands [18] or to changes in the dynamics of the environment [17]. Future work will investigate to what degree these visuomotor feedback gains can be tuned to changes in the properties of the inverted pendulum.

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