Stability of inverted pendulum reveals transition between predictive control and impedance control in grip force modulation

Raz Leib[1], Sae Franklin[2], Justinas Česonis[1] and David W. Franklin[1,3]

***Abstract*— During object manipulation, our sensorimotor system needs to represent the objects dynamics in order to better control it. This is especially important in the case of grip force control where small forces can cause the object to slip from our fingers, and excessive forces can cause fatigue or even damage the object. While the tradeoff between these two constraints is clear for stable objects, such as lifting a soda can, it is less clear how the sensorimotor system adjusts the grip force for unstable objects. For this purpose, we measured the change in the grip force of individual human participants while they stabilize five different lengths of an inverted pendulum. These lengths set different dynamics of the pendulum, ranging in their degree of controllability. We observed two main states during such manipulation, a marginally stable state of the pendulum and a stabilization state in which participants acted to stabilize the system. While during the stabilization state participants increased their applied grip force, for the stable state we observed a mixed behaviour. For small and less controllable pendulums, grip force increased while for larger pendulums, participants could modulate the the grip force according to the anticipated load forces. Based on these results, we suggest that the pendulum dynamics change the control strategy between predictive control and impedance control.**

I. INTRODUCTION

Humans continuously interact with the external world. To do so skillfully, our sensorimotor control system needs the development of predictive forward model that can be used to predict the current and future state of our body [1], [2] and the external world [3]. Previous studies successfully showed that the change in grip force can be used as a measurement of the development of the forward model [4], [5]. However, as the external environment is not always predictable, we need to develop appropriate strategies, task-dependent feedback responses, and predictive models suitable for unpredictable and unstable interactions. Therefore, here we examine the modification of grip force during an unstable balancing task to assess the predictive control of the brain. Specifically, we examined whether healthy human participants modulate their grip force during tool use based on the controllability or stability of the system. We modified a previously developed simulated inverted pendulum [6], [7] on a robotic manipulandum to allow us to measure the change in grip force. By shortening the length of the pendulum, we created a continuous decrease in the predictability of pendulum behaviour. Based on previous studies [8], we hypothesize that for long pendulum lengths, participants could adjust the grip force according to the load force despite the unstable behavior of the system. In this case of short length pendulums, participants would change the control policy from predictive control to a general increase in grip force amplitude in a way that resemble impedance control. In the later case, the coupling between grip and load forces is reduced in order to secure the gripping of the object in light of unexpected load forces.

[1]R. Leib, J. Česonis and D. W. Franklin are with Neuromuscular Diagnostics, Department of Sport and Health Sciences, Technical University of Munich, Munich, 80992 Germany raz.leib@tum.de, justinas.cesonis@tum.de, david.franklin@tum.de

[2]S. Franklin is with the Institute of Cognitive Systems, Department of Electrical and Computer Engineering, Technical University of Munich, Munich, 80333 Germany sae.franklin@tum.de

[3]D.W. Franklin is also with Munich Institute of Robotics and Machine Intelligence (MIRMI), Technical University of Munich, Germany

II. MATERIALS AND METHODS

A. Participants

Six neurologically healthy, right-handed human participants (1 female; aged 37.3 ± 11.5, mean $\pm SD$) took part in the experiment. 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 fingers (thumb and index finger) gripping a force sensor that was attached to the handle of the vBOT robotic interface [9]. Position, velocity and grip 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.

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 [6], [7], [10]. The cart, controlled by the participant, was constrained to a single axis of motion in the x direction approximately 30 cm in front of participants chest by a simulated mechanical channel (stiffness 4000 N/m; damping 2 Ns/m; maximum force value of 25 N). Any force F_x exerted by the pendulum on the cart was applied on the handle in the x direction. For

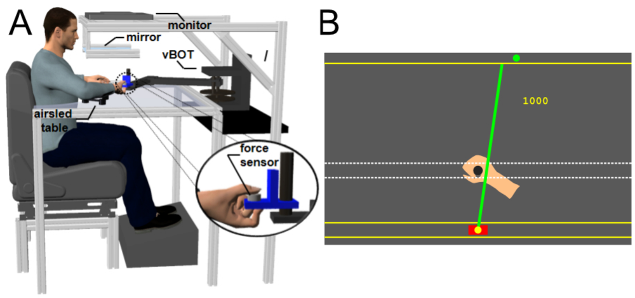

Fig. 1. Experimental setup. (A) Participants sat in front of a robotic manipulandum system (vBOT). They used their thumb and index finger to grasp a force sensor that was mounted on the handle of the robot. The participants arm was supported by an airsled system that reduced friction during movement. The virtual environment was projected on a mirror from a monitor mounted above the movement space. (B) The display of the virtual inverted pendulum. The cart (red square) position was set according to participants hand position. Participants could also observe the angle of the pendulum (green line) and the horizontal position of the pendulum tip (green circle). The score, measuring the deviation from an upright position of the pendulum was displayed after the trial was finished.

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 cart location matched the physical hand position in the x-axis but was shifted 13.0 cm away (y-axis) to maximize the movement range of the participants. 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 (Fig. 1B). 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). Once in the start position, a short beep indicated the start of the trial. This was followed 600 ms later with the pendulum starting to fall with an initial angular velocity of 0.01 rad/s (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 ended when either the pendulum fell over or the pendulum was balanced for 20.0 s. To provide comparable feedback for the participants a score [6] was provided at the end of each trial which depended on the length of time balanced and how upright the pendulum was maintained.

Participants balanced five different lengths L = [0.75 m, 1 m, 1.5 m, 2 m, 4 m] of the pendulum in a blocked design. Each block consisted of twenty trials with the same pendulum length, and two blocks of each pendulum length were provided (once in the first half and once in the second half of the experiment). In total participants performed 10 blocks (200 trials) with the order pseudo-randomized across participants. Between blocks a short break was provided.

D. Analysis

Data was analyzed offline using MATLAB R2021a. Grip force data was low-pass filtered using a 10th order, zero-phase-lag Butterworth filter (15 Hz cutoff). For each trial, we identified segments in the force generated by the robot using a Markov Chain Monte Carlo (MCMC) based algorithm [11]. The algorithm identified transitions between segments based on changes in mean and standard deviation (SD) of the force signal. After identifying the transitions in the signal, we classified the segments according to the force SD. Segments with force SD below 0.2 were considered as stable, segments with SD between 0.2 and 0.5 were considered stabilization state and segments with SD above 0.5 were considered 'unstable'. To average across trials and participants, the time of each segment was normalized by the overall duration of the segment.

III. RESULTS

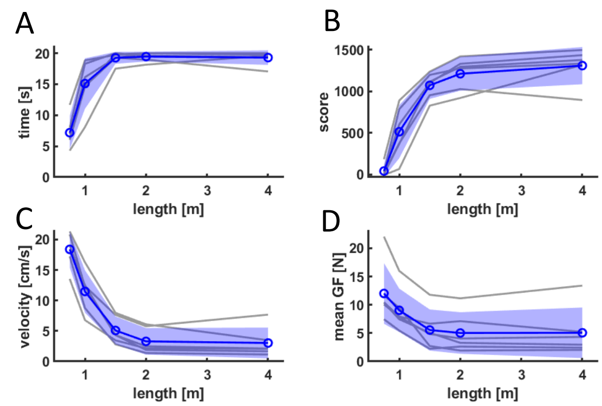

Fig. 2. Participants performance matrices as a function of pendulum length. Time that the pendulum maintained in upright position (A), score (B), cart transient velocity (C), and average applied grip force (D) as a function of the pendulum length. Grey lines represent mean trend for each participant. Blue lines represent the mean value across all participants. Light blue shaded area represents the mean 95% confidence interval calculated using t-distribution.

Participants performance was similar to that of participants in previous studies [6], [7], [10], [12] in which participants directly grasped the handle of the robotic system. Manipulation score, duration and average velocity were not affected by the indirect grasping of the handle (Fig. 2A-C). Using the manipulation of the robotic arm via the force sensor attachment, we observed that in general participants exhibited a reduction in average grip forces for longer pendulum lengths (Fig. 2D). However, averaging grip force over an entire trial did not allow us to fully understand the modulation of applied grip forces. Specifically, what are the changes in grip force when the pendulum is in marginally stable or unstable states? For this purpose, we initially determined different segments based on the characteristics of the load force. We identified three types of states within each trial; marginally stable state, stabilization state, unstable state. The unstable state was characterized by a short duration that resulted in the pendulum falling down. Grip forces during this state were in general very high and did not show any modulation to load forces. The two other states lasted longer and were more relevant for the grip force modulation analysis. Since the duration of the stable state and stabilization phase were different between trials, we initially normalized the time of the grip force signals. An example for this process is depicted in Fig. 3A. We found that for the stable state, the

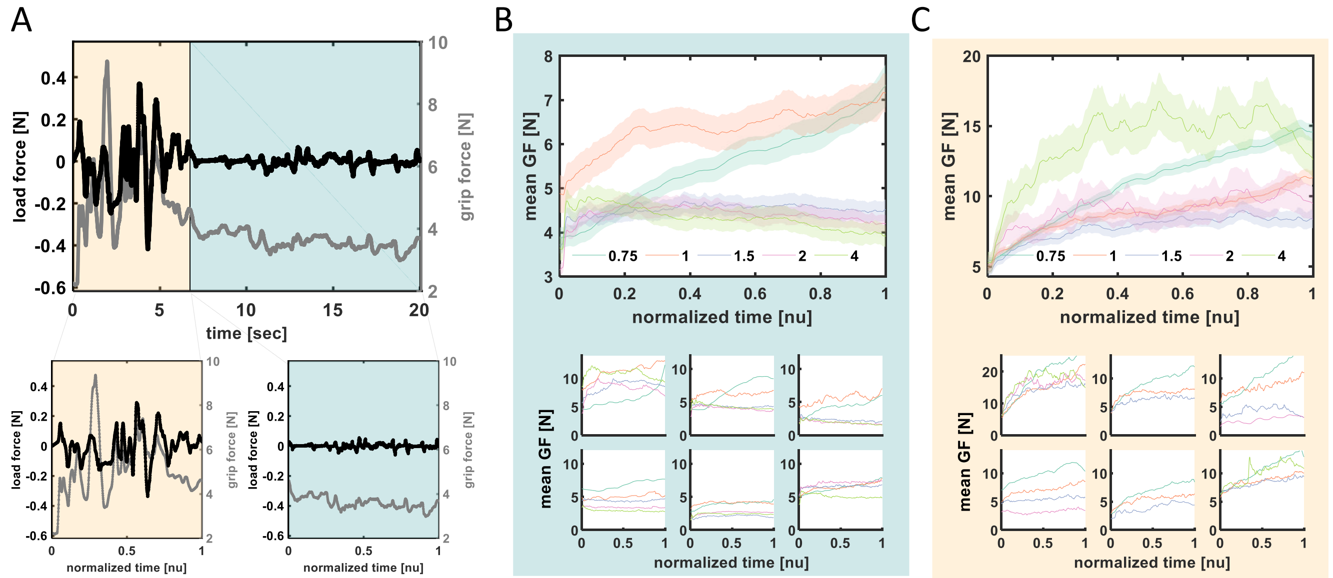

Fig. 3. Average grip force profile for stable state and during stabilization of the pendulum. (A) An example for the segmentation of load and grip force signals into two states: stable state (turquoise) and stabilization phase (yellow). The time of each segment was normalized by the segment overall duration. (B) Upper panel, mean grip force profile as a function of pendulum length for the stable state across all participants. Different colors represent each pendulum length. Shaded area represents the standard error. Bottom panels, mean grip force profile for the stable state of each participant. (C) Same as in B but for the stabilization phase. Note that the mean grip force profile for pendulum length 4 was calculated according to only two participants since all other participants could immediately stabilize the pendulum and hence had no stabilization phase when manipulating the pendulum with this length.

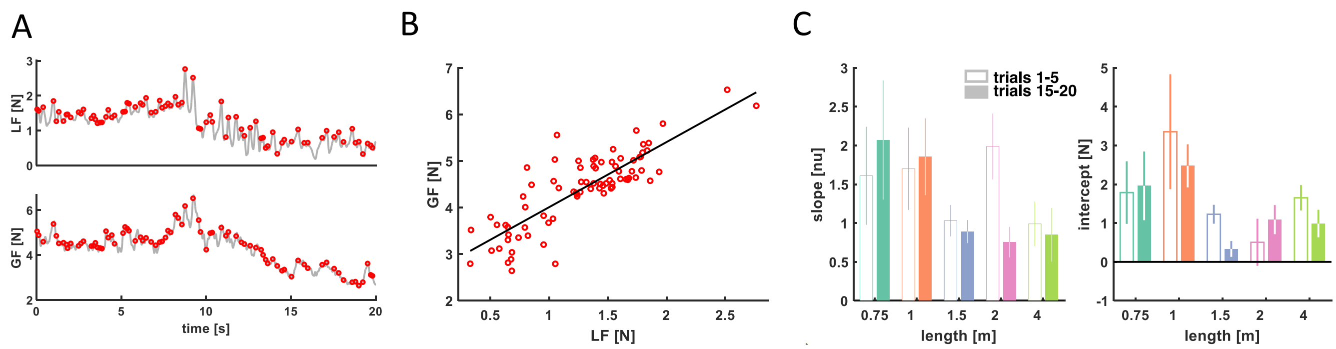

Fig. 4. Grip force modulation according to load force for the stable state. (A) Upper panel, example of a load force (LF) profile during a single trial. Red dots represent the maximum points in the signal. Bottom panel, grip force (GF) profile for the same example trial. Red dots represent the GF values measured at the same times of the maximum LF values. (B) The GF values plotted as a function of the matching LF values from the example signals in (A). Black line represents a regression line fitted to these points. (C) The process described in panels A and B was repeated for all trials and for all participants. Mean slope value (left panel) and mean intercept value (right panel). Our experimental design included twenty consecutive trials in which participants interacted with only one value of pendulum length. We calculated the slope and intercept mean value for the first five trials (clear bars) and last five trials (filled bars) for each pendulum length. Error bars represent the standard deviation.

averaged grip force signals had two different patterns (Fig. 3B). For pendulum lengths 1.5, 2 and 4, the averaged grip force had a small amplitude decrease while for pendulum lengths 0.75 and 1, we found an increase in grip force magnitude as time progressed within the stage. For the stabilization phase, we observed an increase in grip force for all pendulum lengths, and this increase was higher for short lengths compared with high lengths (Fig. 3C). The averaged grip force signal for pendulum length 4 seems to be higher than all the other lengths, however, this averaged profile was calculated based on fewer traces compared with other lengths since participants were mostly in the stable state and not in the stabilization state during interaction with this pendulum length (Fig. 3C bottom panels). While the averaged signals provided a general trend of grip force magnitude within a trial, it does not provide any information regarding the modulation of grip force between trials or about the coupling with load forces. To examine how grip forces changed between trials and how they were coupled with load force, we used regression analysis between load force (LF) and grip force (GF). Based on previous results [4], [8] of grip force analysis during interactions with stable objects and the magnitude analysis reported here, we expected to see a reduction in grip force across trials for the stable state in which it is more likely to predict the load forces. We focused on each block of trials in which participants interacted with one pendulum length. For each trial, we identified the maximum points in the LF signal. These points were coupled with the grip force measured at the same time [13] (Fig. 4A) and we fitted a regression line for these points in the GF-LF plane (Fig. 4B). This process was repeated across trials and participants. From the regression line we extracted the slope value, which indicates the amount of change in the grip force per change in the load force, and the intercept point, which indicates the general elevation of baseline grip force. For each pendulum length we calculated the average slope and intercept values across participants for the initial five trials and for the last five trials within each block of trials (Fig. 4C). We found that for the 1.5, 2, and 4 pendulum lengths the slope value at the last trials of the block were around a value of 1 indicating that participants could anticipate the load forces values during manipulation and adjust their grip force accordingly with a safety margin as indicated by a positive value of the intercept point. For short pendulum lengths, we found that the slope value was higher than a value of 1 indicating that participants applied excessive grip force to the experienced load force.

IV. DISCUSSION & CONCLUSIONS

We found that grip force modulation depends on both the characteristics of the pendulum and the state of the manipulation. When the pendulum was in a marginally stable state, participants were able to reduce the general grip force and adjust it to the load force for large, but not for small, pendulum lengths. During stabilization of the pendulum, participants exhibited a general increase in grip force. The reduction in grip force fits with the general improved performance of participants when manipulating long lengths pendulums. Participants were able to predict the pendulum movement, and hence the generated load force, and adjust both their movements as well as the grip force despite the instability of the pendulum, in contrast to other types of instabilities [14]. During manipulation of the object, the controller can adjust the grip forces according to the predictions of a forward model. The forward model needs to represent the unstable dynamics and predict the forces generated by the pendulum so it can avoid slippage of the object from the participants' fingers. Contrary to this reduction during the stable state, for small length pendulums and during the stabilization phase participants increased their applied grip force. During the stabilization phase the load forces variability increases which was previously reported to cause a general increase in the safety margin of applied grip forces [8]. Due to the increased variability, the motor system might rely less on predictive mechanism and adopt an impedance control approach that is more suitable for unstable and less predictable environments [15]. The increase grip force suggest that the contraction of the fingers around the object increases in a similar way to elevated co-contraction around a joint during hand movements in unstable environments. An alternative explanation to the modulation in grip force can be due to the basic characteristics of the grip force control. While it is natural to think that applied grip force is varying in continuous fashion and hence can change on a moment-to-moment basis, applied grip force can have an intermittent nature [16]. In such control architecture, sensory feedback needed to update the grip force policy, might be available to the controller only at spare time points which can decrease the efficiency of the controller to apply grip force that is coupled to the load force. As a result, the control policy can change into a general increase in the safety margin of grip force while neglecting the instantaneous modulation of the signal so it will match possible load force fluctuations. In future studies we aim to examine this alternative suggestion and the structure of such proposed intermittent controller [17] using grip force analysis.

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