Robust Postural Stabilization with a Biomimetic Hierarchical Control Architecture

Adrián Fernández Amil[1,2], Giovanni Maffei[3,5],
Jordi-Ysard Puigbò[1,2,3], Xerxes D. Arsiwalla[1,2,3],
and Paul F. M. J. Verschure[1,2,3,4](✉)

[1] Institute for Bioengineering of Catalonia (IBEC), Barcelona, Spain
pverschure@ibecbarcelona.eu
[2] Barcelona Institute of Science and Technology (BIST), Barcelona, Spain
[3] Technology Department, University Pompeu Fabra, Barcelona, Spain
[4] Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain
[5] Alpha, Telefónica, Barcelona, Spain

Abstract. Fast online corrections during anticipatory movements are a signature of robustness in biological motor control. In this regard, a previous study suggested that anticipatory postural control can be recast as a sensory-sensory predictive process, where hierarchically connected cerebellar microcircuits reflect the causal sequence of events preceding a postural disturbance. Hence, error monitoring signals from higher sensory layers inform lower layers about violations of expectations, affording fast corrections when the normal sequence is broken. Here we generalize this insight and prove that the proposed hierarchical control architecture can deal with different types of alterations in the causal structure of the environment, therefore extending the limits of performance.

Keywords: Cerebellum · Anticipatory control · Robustness · Control architecture

1 Introduction

Anticipation allows humans to maintain their bodies in desired states even when external disturbances are present [1]. That is, provided that perturbations are preceded by sensory cues, well-timed anticipatory actions are acquired to efficiently counteract them, enhancing the controllability of body posture [2]. However, after the acquisition, a person incurs in the risk of over- or under-anticipating if the perturbation or the preceding signal do not match the expectations. Therefore, theories of anticipatory motor control must account for the fast corrections needed to keep stability under variable conditions. In a previous study [3], a novel cerebellar-based control scheme called Hierarchical Sensory Predictive Control (HSPC) was compared to another architecture based on the standard theory of motor adaptation, Feedback Error Learning (FEL) [4]. Whereas HSPC casts the anticipatory control as a predictive process in the

U. Martinez-Hernandez et al. (Eds.): Living Machines 2019, LNAI 11556, pp. 321–324, 2019.
https://doi.org/10.1007/978-3-030-24741-6_29

sensory domain, FEL acts in the motor domain (see Fig. 1, bottom). Importantly, in HSPC, the sensory prediction error (e_d in Fig. 1) is not only used for learning, but also as an error-correction signal that informs about violations of sensory expectations. This mechanism, absent in FEL, explains the early online corrections of over-anticipations seen in "catch trials" with humans (i.e. the preceding cue is present, but the perturbation is not delivered) [3]. Here we test and validate the generality and robustness of this error-correction mechanism for a wider range of conditions, using a variation of the classical inverted pendulum problem in control theory as our reference system to compare the HSPC and FEL architectures' generalization capabilities.

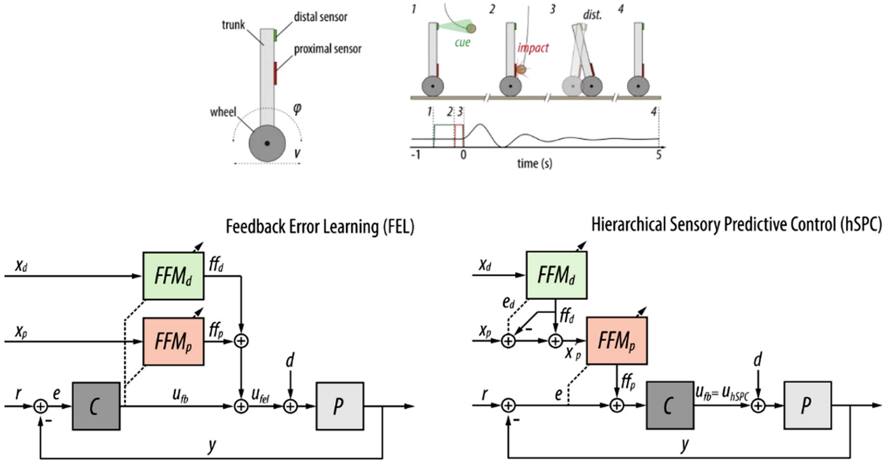

Fig. 1. (Top) Simulated inverted pendulum during a normal training trial. 1- distal sensing (vision). 2-proximal sensing (proprioception). 3-sensing of the angular displacement (vestibular). 4-postural stabilization. **(Bottom left)** Feedback Error Learning (FEL) architecture. Both feed-forward modules send anticipatory motor commands to the plant and learn from the output of the feedback controller. **(Bottom right)** Hierarchical Sensory Predictive Control (HSPC) architecture. The distal module sends early sensory predictions to the proximal module and learns from the sensory prediction error. The error is also added to the anticipated prediction as input to the proximal module, acting as an error correction signal. Finally, the proximal module sends *counterfactual* errors to the feedback controller and learns from the error in angle.

2 Methods

We use the same setup as in [3]. A simulated inverted pendulum was driven by a Proportional-Derivative (PD) controller by providing torque at its base. The sensory feedback corresponds to the delayed error in angle with respect to the vertical. Besides the feedback loop, two feed-forward modules (distal and proximal), acting as cerebellar adaptive filters [5], are arranged according to a sensory prediction (HSPC) or motor anticipation (FEL) hypothesis (see Fig. 1, bottom). Importantly, all the feed-forward modules have the same set of alpha-like temporal basis functions and are updated following the same learning rule: the Least Mean Squares (LMS) [6], with an eligibility trace to account for the delays between signals [7]. The experiment goes as follows (see Fig. 1, top). First, the agents (HSPC- and FEL-based) are trained for 100 trials with the same cue and perturbation. The distal cue (i.e. vision) is briefly presented before the perturbation is delivered. The perturbation itself is modeled as a brief constant force of 100 N at the center of mass of the pendulum. The proximal signal (i.e. proprioception) follows the timings of the force, with some delay. Both the distal and proprioceptive signals are modeled as rectangular functions, with magnitude 1. After training, both agents are tested without further learning for a wide range of forces and distal cues, covering an important portion of the Cue-Force space. Thus, performance surfaces are obtained, that go beyond the typical test with the catch trial.

3 Results and Discussion

As can be seen from Fig. 2 (top), both FEL and HSPC architectures acquire successful anticipatory actions that minimize the error caused by the perturbation, compared to before training (the "naive condition"). Moreover, they do so at an equal pace (shown by the acquisition curves). Furthermore, the effects of the early error-correction mechanism in HSPC can be seen during the catch trial (Fig. 2, bottom), whereas FEL incurs in a bigger self-generated peak angular error that the feedback is then forced to counteract afterward. Finally, from Fig. 3 it is shown that HSPC's robustness capabilities seen in the catch trial [3] generalize to a much wider range of conditions. The surfaces or generalization gradients show the performance landscape for both architectures, with HSPC's being flatter than FEL's. Therefore, the ("plant-agnostic") error-correction mechanism makes the hierarchical control scheme to work better under previously unseen environments, making it a more robust architecture without having

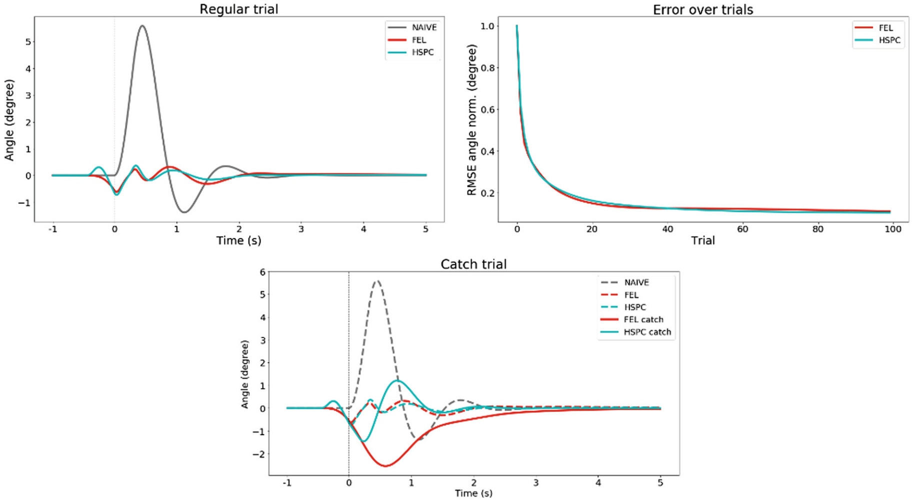

Fig. 2. **(Top)** Behavior (angle) of HSPC and FEL in first ("naive", feedback response) and last (trained) regular training trials (cue = 1, force = 100 N at 0 s); and the acquisition curves during training (in cumulative RMSE of angle). **(Bottom)** Behavior in catch trials (cue = 1, force = 0 N).

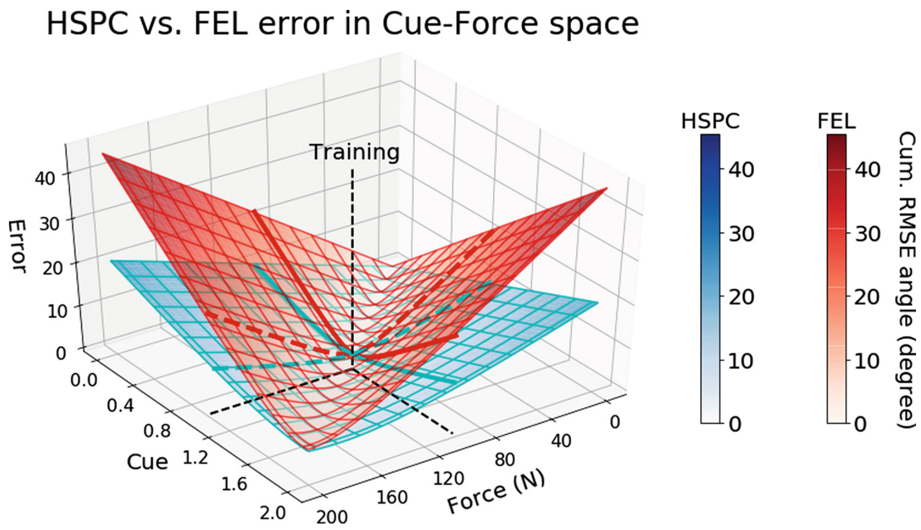

Fig. 3. Generalization gradients of FEL and HSPC for a wide range of distal cues and forces. The lines represent slices made to the surfaces at cue = 1 (dashed lines) and force = 100 N (solid lines). The errors are measured as the cumulative RMSE angle (in degrees) during the trials.

to sacrifice top performance. However, a systematic analysis of both architectures in terms of the performance-robustness trade-off is still lacking. Hence, in future work we will test both control schemes under stochastic environments, to see how uncertainty and variability affect their learning dynamics and generalization capabilities.

Acknowledgments. The work presented in this paper was supported by the European Commission under contract H2020-820742 HR-Recycler.

References

1. Shadmehr, R., Smith, M.A., Krakauer, J.W.: Error correction, sensory prediction, and adaptation in motor control. Annu. Rev. Neurosci. **33**, 89–108 (2010)
2. Massion, J.: Postural control system. Curr. Opin. Neurobiol. **4**(6), 877–887 (1994)
3. Maffei, G., Herreros, I., Sánchez-Fibla, M., Friston, K.J., Verschure, P.F.M.J.: The perceptual shaping of anticipatory actions. Proc. R. Soc. B: Biol. Sci. **2017**(284), 1–9 (1869)
4. Kawato, M.: Internal models for motor control and trajectory planning. Curr. Opin. Neurobiol. **9**(6), 718–727 (1999)
5. Dean, P., Porrill, J., Ekerot, C.-F., Jörntell, H.: The cerebellar microcircuit as an adaptive filter: experimental and computational evidence. Nat. Rev. Neurosci. **11**, 30–43 (2009)
6. Widrow, B., Stearns, S.D.: Adaptive Signal Processing. Prentice-Hall Inc., Englewood Cliffs (1985)
7. Herreros, I., Arsiwalla, XD., Verschure, P.F.M.J.: A forward model at Purkinje cell synapses facilitates cerebellar anticipatory control. In: Proceedings in Advances in Neural Information Processing Systems, pp. 3828–3836 (2016)