BJMB
Brazilian Journal of Motor Behavior

Current Opinion

Shared internal models between feedforward and feedback control

RODRIGO S. MAEDA[1-3] | J. ANDREW PRUSZYNSKI[1-4]

[1] Brain and Mind Institute, Western University, London, Ontario, Canada.
[2] Robarts Research Institute, Western University, London, Ontario, Canada.
[3] Department of Psychology, Western University, London, Ontario, Canada.
[4] Department of Physiology and Pharmacology, Western University, London, Ontario, Canada.

Correspondence to: Dr. J. Andrew Pruszynski, Robarts Research Institute, Western University, 1151 Richmond St. N., Rm 1254A, London, ON, N6A 5B7, Canada
email: andrew.pruszynski@uwo.ca
https://doi.org/10.20338/bjmb.v14i5.211

PUBLICATION DATA
Received 28 10 2020
Accepted 27 11 2020
Published 01 12 2020

An influential idea in sensorimotor neuroscience is that the nervous system relies on a set of internal predictions (i.e., an internal model) to generate feedforward (i.e., voluntary) motor commands that account for delayed and noisy sensory feedback, and that can adapt to new altered environments.[1] This idea has recently been extended to a class of rapid feedback responses (i.e., long-latency stretch reflexes) that are partially mediated by neural structures that contribute to voluntary motor control, and which have to deal with the same factors.[2,3] In this current opinion article, we present some evidence that feedforward motor commands and these fast feedback responses share an internal model for motor control.

A classic method to study internal models during upper-limb movements involves having participants reach towards visually presented targets in the presence of an external force field. In the absence of the force field, participants easily perform straight movements to a target. However, upon the introduction of the force field, movements are initially deviated, as participants try to perform the same straight reach to the target. Participants gradually learn the dynamics of the novel force environment and return to straight reaches by modifying their motor commands predictively to compensate for the force field.[1] A similar approach has been used to test whether such learning also influences fast feedback responses to mechanical perturbations applied to the arm. After learning, when a perturbation is delivered just prior to entering the force field, fast feedback responses are increased, similar to the increase observed in muscle activity after learning to reach in the force field.[4] These results support the notion that motor learning during reaching transfers to feedback responses.

We recently took another approach to this question by leveraging intersegmental arm dynamics. Specifically, the fact that torques applied at one joint produces movement at multiple joints.[3] Previous work has demonstrated that when generating single-joint elbow movements and when responding to mechanical perturbations that create pure elbow motion with a robotic exoskeleton, the nervous system makes use of an internal model of the arm's dynamics. This allows generating predictive shoulder muscle activity and robust shoulder feedback responses to counter the underlying torques that arise at the shoulder joint because of forearm rotation about the elbow joint.[2,3] One way of determining how the nervous system accounts for arm dynamics is by altering the normal mapping between joint torques and joint motion. When we did this experiment, we found that generating pure elbow movements with the shoulder joint fixed (i.e., altered arm dynamics) causes people to reduce shoulder muscle activity during reaching and that such learning transfers to feedback responses, even though these feedback responses were never directly trained.[5] This learning and transfer are appropriate and efficient because fixing the shoulder joint eliminates the interaction torques that arise at the shoulder when the forearm rotates and thus removes the need to recruit shoulder muscles. Such transfer from feedforward motor commands to feedback responses is thought to take place because of their shared neural circuits at the level of the spinal cord, brainstem, and cortex.[6]

The presence of shared neural resources also predicts the transfer from feedback responses to feedforward motor commands. To answer this question, we used two approaches to elicit learning in feedback responses without engaging associated voluntary responses following perturbations: 1) we applied very short mechanical perturbations and 2) we instructed participants to not respond to them in the course of learning shoulder fixation.[7] We found that fixing the shoulder joint leads to a reduction in shoulder feedback responses (i.e., learning arm dynamics) with a minimal engagement of voluntary motor responses in the learning process. Moreover, we found that this reduction in feedback responses transfers to feedforward motor commands during elbow reaching, even though participants never practiced reaching with the shoulder fixed. These results support the notion of a bidirectional transfer of motor learning between feedforward and feedback control.

An important avenue of future research is determining the extent of such bidirectional motor learning and transfer between feedforward and feedback control at the behavioral and neurophysiological levels. At the behavioral level, it is important to find out whether the nervous system shares internal models for a range of motor tasks or whether the shared internal models are restricted to some specific situations, such as after learning altered force-fields or visuomotor environments. At the neurophysiological level, there are neural nodes that are particularly engaged during both feedforward generation of motor commands and feedback responses.[8,9] Future work should focus on examining neural activity in these nodes, as a means of determining which of them provides the neural substrate for shared internal models.[10]

REFERENCES

1. Shadmehr R, Smith MA, Krakauer JW. Error correction, sensory prediction, and adaptation in motor control. *Annu Rev Neurosci*. 2010;33:89–108. DOI: 10.1146/annurev-neuro-060909-153135
2. Kurtzer IL, Pruszynski JA, Scott SH. Long-Latency Reflexes of the Human Arm Reflect an Internal Model of Limb Dynamics. *Curr Biol*. 2008;18:449–453. DOI: 10.1016/j.cub.2008.02.053
3. Maeda RS, Cluff T, Gribble PL, Pruszynski JA. Compensating for intersegmental dynamics across the shoulder, elbow, and wrist joints during feedforward and feedback control. *J Neurophysiol*. 2017;118:1984–1997. DOI: 10.1152/jn.00178.2017

4. Ahmadi-Pajouh MA, Towhidkhah F, Shadmehr R. Preparing to reach: selecting an adaptive long-latency feedback controller. *J Neurosci*. 2012;32:9537–9545. DOI: 10.1523/JNEUROSCI.4275-11.2012
5. Maeda RS, Cluff T, Gribble PL, Pruszynski JA. Feedforward and feedback control share an internal model of the arm's dynamics. *J Neurosci*. 2018;38:10505–10514. DOI: 10.1523/JNEUROSCI.1709-18.2018
6. Scott SH. A Functional Taxonomy of Bottom-Up Sensory Feedback Processing for Motor Actions.*Trends Neurosci*. 2016;39:512–526. DOI: 10.1016/j.tins.2016.06.001
7. Maeda RS, Gribble PL, Pruszynski JA. Learning new feedforward motor commands based on feedback responses. *Curr Biol*. 2020;30:1941–1948. DOI: 10.1016/j.cub.2020.03.005
8. Pruszynski JA, Kurtzer I, Nashed JY. et al. Primary motor cortex underlies multi-joint integration for fast feedback control. *Nature*. 2011;478:387–390. DOI: 10.1038/nature10436
9. Gritsenko V, Kalaska JF, Cisek P. Descending corticospinal control of intersegmental dynamics. *J Neurosci*. 2011;31:11968–11979. DOI: 10.1523/JNEUROSCI.0132-11.2011
10. Maeda RS, Kersten R, Pruszynski JA. Shared internal models for feedforward and feedback control of arm dynamics in non-human primates. *bioRxiv*. 2020;1–23. DOI: 10.1101/2020.04.05.026757

Citation: Maeda RS, Pruszynski JA. Shared internal models between feedforward and feedback control. BJMB. 2020: 14(5): 134-136.
Editors: Dr Fabio Augusto Barbieri - São Paulo State University (UNESP), Bauru, SP, Brazil; Dr José Angelo Barela - São Paulo State University (UNESP), Rio Claro, SP, Brazil; Dr Natalia Madalena Rinaldi - Federal University of Espírito Santo (UFES), Vitória, ES, Brazil.
Section Editors (Current Opinion): Dr Luis Augusto Teixeira - University of São Paulo (USP), São Paulo, SP, Brazil; Dr Tibor Hortobágyi - University of Groningen, The Netherlands; Dr Renato de Moraes - University of São Paulo (USP), Ribeirão Preto, SP, Brazil.

Funding: This work was supported by a grant from the Canadian Institutes of Health Research (Foundation Grant to J.A.P.) and by the BrainsCAN program at Western University. R.S.M. received a salary award from Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq/Brazil). J.A.P. received a salary award from the Canada Research Chairs program.
Competing interests: The authors have declared that no competing interests exist.
DOI: https://doi.org/10.20338/bjmb.v14i5.211