Spinal stretch reflexes support efficient hand control

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Motor behaviour is most efficiently controlled by correcting only disturbances that influence task success. It is currently thought that such control is computed within a transcortical feedback pathway. Here we show that, for postural hand control, even the fastest spinal feedback pathway can produce efficient corrective responses, forcing a re-evaluation of how the nervous system derives the control laws that support motor behavior.

Real-world actions require active control of many joints in the presence of internal and external disturbances. The simplest way for the nervous system to counteract disturbances is to ensure that all the joints remain at some specific set of reference positions by independently correcting deviations at each joint. However, a better way for the nervous system to counteract disturbances is to take advantage of musculoskeletal redundancy—correcting only joint deviations to the degree that they interfere with task success[1].

Many behavioural studies have shown that the nervous system adheres to this more sophisticated control scheme. For example, when people reach to grasp an object, errors introduced by experimentally perturbing one finger are not only corrected by responses at the perturbed finger but at all the fingers that help to govern grasp aperture[2]. A key outstanding question in sensorimotor neuroscience is which neural circuits implement the sophisticated control laws that produce such efficient corrective responses[3]. Sixty years of work, primarily focusing on reaching actions, indicate that spinal circuits do not perform the requisite computations and that this capacity may be a specialization of a transcortical feedback pathway through primary motor cortex and other cortical regions involved in the production of voluntary movement[4–7].

Here we show that, in the context of postural hand control, even the fastest spinal feedback pathway can produce sophisticated control solutions. In our experiments, participants maintained their hand at a spatial target while we applied small mechanical perturbations to their elbow and wrist joints. We chose mechanical perturbations that moved the participant's hand away from the target to varying degrees, but critically, we ensured that the perturbation that yielded the largest hand displacement did so with the least elbow rotation. We found that spinal stretch reflexes of elbow muscles were tuned to the hand's displacement relative to the target, rather than the amount of elbow rotation, and thus the amount that the muscle was stretched. We then dissociated wrist rotation from how the hand moved relative to the target, by participants adopting two different arm orientations. In this arrangement, the same mechanical perturbation at the wrist moved the hand away from the target in one arm orientation but towards the target in the other arm orientation. We again found that spinal stretch reflexes at the elbow were tuned to hand displacement rather than elbow rotation. In fact,

changing the arm's orientation reversed the pattern of spinal stretch reflexes at the elbow in a way that was appropriate for returning the hand to the target. Taken together, these findings reveal that this spinal feedback pathway is more sophisticated than previously thought — capable of flexibly integrating inputs from multiple muscles to produce efficient corrective responses that take advantage of musculoskeletal redundancy.

In our first experiment, participants ($n=25$) grasped the handle of a robotic exoskeleton and placed their hand at a central target while countering small flexion loads at the elbow and wrist. The robot then mechanically flexed their elbow, stretching the triceps muscle, and simultaneously flexed, extended, or did not alter the angle of their wrist (Fig. 1a and Supplementary Fig. 1a). Note that although the same elbow perturbation was always applied, the simultaneous wrist perturbations generated different amounts of elbow rotation because of interaction torques between limb segments. Critically, all of the mechanical perturbations moved the participant's hand away from the target and the hand was displaced furthest from the target when the elbow was rotated the least, and the hand remained closest when the elbow was rotated the most (Fig. 1b–f).

Participants were instructed to counteract the perturbation and return their hand to the target quickly and accurately. They did so not by simply returning their joints to their initial positions, but by simultaneously extending their elbow and wrist joints in a coordinated fashion (Fig. 1b,c). We found that the triceps spinal stretch reflex (that is, mean electromyography (EMG) activity 25–50 ms post perturbation) was tuned to the distance that the hand was displaced from the target, and not the amount the elbow was flexed ($F(2,48)=103.5$, $p<0.001$, $\eta^2_{partial}=0.81$; post-hoc trend analysis: linear $F(1,24)=127.04$, $p<0.001$, $\eta^2_{partial}=0.84$; quadratic $F(1,24)=2.05$, $p=0.17$, $\eta^2_{partial}=0.08$). In fact, the magnitude of the triceps spinal stretch reflex was largest when the triceps muscle was stretched the least, and even inhibited relative to baseline when it was stretched the most (Fig. 1e–h). In our second experiment, participants ($n=20$) placed their hand on the central target while countering small extension loads at the elbow and wrist. The robot then mechanically extended the elbow, stretching the biceps muscle, and simultaneously flexed, extended, or did not alter the angle of their wrist (Supplementary Fig. 1b). Similar to the triceps, the biceps spinal stretch reflex was tuned to the hand's displacement from the target, and not to the amount that the elbow was extended (Supplementary Fig. 2).

So far, we have demonstrated that the spinal stretch reflexes of elbow muscles are tuned to the hand's displacement from the target, and not elbow rotation. These results run counter to many experiments showing that spinal stretch reflexes are not immediately

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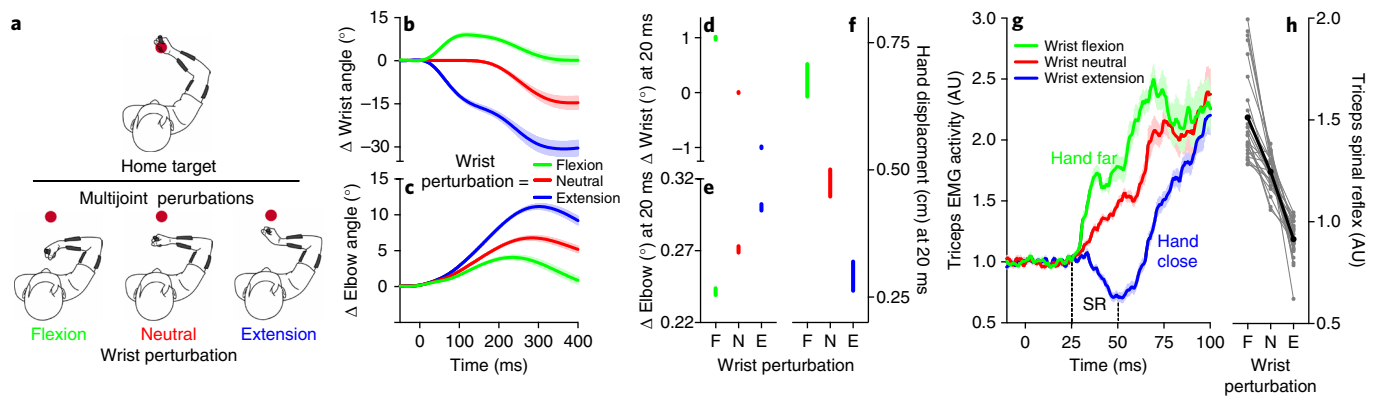
Fig. 1 | Spinal stretch reflex is tuned to hand displacement. a, Elbow flexion perturbation and simultaneous wrist flexion perturbation (bottom left), no wrist perturbation (bottom centre) and wrist extension perturbation (bottom right) displace the hand from the target (red dot, top centre). **b**, Mean change in wrist angle aligned to perturbation onset. Green and blue traces represent perturbations that flexed and extended the wrist, respectively. Red trace reflects trials in which no mechanical perturbation was applied to the wrist. Shading represents ±1 s.e.m. **c**, Same format as **b**, but for mean change in elbow angle. **d**, 95% confidence interval centred on the group mean change in wrist angle 20 ms after perturbation onset when the wrist was flexed (F), not perturbed (N) or extended (E). **e**, Same format as **d**, but for change in elbow angle. **f**, Same format as **d**, but for hand displacement from the target. **g**, Same format as **b**, but for mean rectified triceps EMG activity. SR denotes the epoch associated with the spinal stretch reflex. **h**, Mean triceps EMG activity in the spinal stretch reflex epoch for the three wrist perturbations. Thin grey lines represent individual participants and the thick black line represents the group mean. All panels represent data from experiment 1 ($n = 25$).

modulated by task goals[8]. In our third experiment we tested whether, in our paradigm, the triceps spinal stretch reflex is influenced by task goals. Participants ($n = 15$) completed two blocks of trials in which the same loads from the first experiment were applied. In one block of trials, participants were instructed to return their hand quickly to the target following the perturbation, and in the other block they were instructed to 'not intervene' following the perturbation. What is typically observed is that spinal stretch reflexes are not modulated by the intended action, whereas responses that include inputs from a transcortical feedback pathway (that is, the long-latency stretch reflex: muscle activity 50–100 ms post perturbation) are influenced[8]. Our data are consistent with this classical finding. Specifically, the magnitude of the triceps spinal stretch reflex was not influenced by the intended action when the wrist was flexed, not perturbed, or extended, whereas the triceps long-latency stretch reflex was influenced by the intended action for all three wrist perturbations (Supplementary Fig. 3).

The functional modulation of the spinal stretch reflexes we have so far described must arise because the motor neurons that innervate elbow muscles integrate afferent feedback from both the elbow and the wrist. Recall that in the first experiment we applied a flexion load at the wrist prior to the perturbation — a manipulation that presumably increases the sensitivity of wrist extensor muscle spindles and decreases the sensitivity of wrist flexor muscle spindles via alpha–gamma coactivation[9]. In contrast, in the second experiment we applied a small extension load at the wrist prior to the perturbation — a manipulation that increases the sensitivity of wrist flexor muscle spindles and decreases the sensitivity of wrist extensor muscle spindles. Our results above suggest that it is the wrist extensor (flexor) muscles that provide the source of afferent feedback to functionally tune the triceps (biceps) spinal stretch reflex. If true, then inhibiting the wrist extensors should decrease or eliminate the functional tuning of the triceps spinal stretch reflex, and inhibiting the wrist flexors should decrease or eliminate the functional tuning of the biceps spinal stretch reflex.

In our fourth experiment, participants ($n = 20$) countered a small flexion load at the elbow and a small extension load at the wrist, inhibiting the afferent output from the wrist extensor muscles. The robot then mechanically flexed the elbow and simultaneously flexed or extended the wrist (Supplementary Fig. 1c). Consistent with our prediction above, we found that the triceps spinal stretch reflex was no longer tuned to the hand's displacement from the target, but to the degree that the elbow was flexed, $t(19) = -3.43$, $p = 0.003$, Cohen's $d = 0.77$, 95% CI [$-0.19 -0.05$] (Fig. 2a,b). In our fifth experiment, participants ($n = 15$) countered a small extension load at the elbow and a small flexion load at the wrist, inhibiting the afferent output from the wrist flexors muscles. The robot then extended the elbow mechanically, stretching the biceps, and simultaneously flexed or extended the wrist (Supplementary Fig. 1d). Similar to our fourth experiment, we found that the biceps spinal stretch reflex was no longer tuned to the hand's displacement relative to the target (Supplementary Fig. 4).

The experiments above show that the functional tuning of the spinal stretch reflex of triceps and biceps is sensitive to the pre-perturbation state of the wrist extensor and wrist flexor muscles, respectively. In our sixth experiment we tested whether functional tuning can still be elicited in the triceps muscle when the wrist extensors are in a neutral, perhaps a more natural, state — neither excited nor inhibited — prior to the perturbation (Supplementary Fig. 1e). Participants ($n = 15$) completed the same protocol as experiment 4, but with no load applied to the wrist before the perturbation. Results from this experiment showed that the triceps spinal stretch reflex was once again tuned to the hand's displacement from its initial location, $t(14) = 3.75$, $p = 0.002$, Cohen's $d = 0.97$, 95% CI [0.08 0.30] (Fig. 2c,d) and, as expected, there was less modulation than when the wrist extensors were pre-excited prior to perturbation onset (Fig. 1e–h).

In experiments 4 and 5, we eliminated the functional tuning of the triceps and biceps spinal stretch reflexes by decreasing the sensitivity of wrist extensor and flexor muscle spindles, respectively. This functional tuning, therefore, must arise because the motor neurons innervating specific elbow muscles utilize afferent feedback from specific wrist muscles. However, if this wrist feedback is hardwired—only acting directly on the motor neurons innervating specific elbow muscles—the evoked reflexes would be counterproductive for controlling hand position when participants change the orientation of their arm.

We ruled out this possibility in a seventh experiment. Participants ($n = 15$) completed one block of trials by grasping the robot's handle naturally, with their thumb pointing upwards (that is, 'upright')
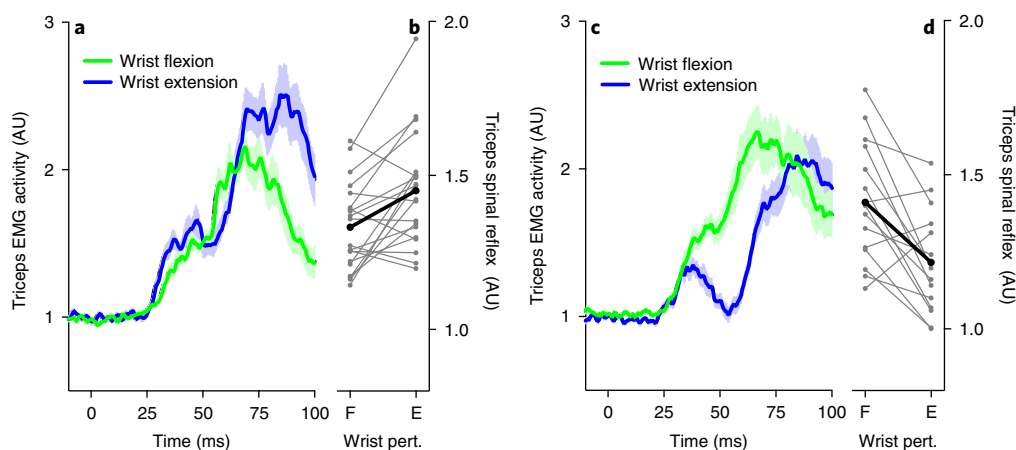
Fig. 2 | Determining the source of wrist afferent feedback that tunes the elbow spinal stretch reflex. a, Mean rectified triceps EMG activity when the wrist extensor muscles were inhibited prior to the mechanical perturbation. Green and blue traces reflect wrist perturbations that flexed and extended the wrist, respectively. Data are aligned to perturbation onset. Shading reflects ±1 s.e.m. **b**, Mean rectified triceps EMG activity in the spinal stretch reflex epoch when the wrist extensor muscles were inhibited prior to the mechanical perturbation (pert.) that flexed (F) or extended (E) the wrist. Thin grey lines represent individual participants and the thick black line represents the group mean. **c,d**, Same format as **a** and **b** but for when the wrist extensor muscles were neither excited nor inhibited prior to the perturbation. Panels **a** and **b** represent data from experiment 4 ($n = 15$), and panels **c** and **d** represent data from experiment 6 ($n = 15$).

and a second block by grasping the handle with their thumb pointing downwards (that is, 'flipped'; Fig. 3a). For both blocks of trials, participants countered small flexion loads placed on the elbow and wrist, and then moved their hand to the central target. After a brief delay the robot flexed their elbow, and simultaneously either flexed or extended their wrist (Supplementary Fig. 1f). Participants were instructed to counteract the perturbation by returning their hand to the target quickly and accurately. Critically, the different arm orientations dissociated how wrist rotation translated to hand movement relative to the target. As a result, wrist flexion perturbations displaced the hand further from the target when participants adopted the upright compared to the flipped orientation, and wrist extension perturbations displaced the hand further from the target when participants adopted the flipped compared to the upright orientation (Fig. 3f,g).

Participants readily changed how they coordinated their elbow and wrist joints as a function of arm orientation (Fig. 3b–e), and the different arm orientations did not qualitatively influence how spinal stretch reflexes were evoked from the wrist extensor muscles (Supplementary Fig. 5). Strikingly, the triceps spinal stretch reflex was again tuned to the hand's displacement from the target rather than the elbow's rotation (wrist flexion, $t(14) = 6.05$, $p < 0.001$, Cohen's $d = 1.56$, 95% CI [0.22 0.47]; wrist extension, $t(14) = -8.66$, $p < 0.001$, Cohen's $d = 2.24$, 95% CI [0.33 0.55]). In fact, changing the arm's orientation diametrically altered the pattern of the triceps spinal stretch reflex and did so in a way that was appropriate for returning the hand to its initial location (Fig. 3h–k).

Regulating the length of individual muscles is the simplest way to stabilize the body against disturbances and such a control scheme could be implemented by monosynaptic and homonymous connections between muscle spindles and motor neurons that arise from and target the same muscle — the typical description of the architecture of the spinal stretch reflex pathway[10]. Our results reveal that the neural pathway that generates the spinal stretch reflex can also produce more sophisticated control solutions when stabilizing the hand in the presence of external disturbances. The triceps and biceps spinal stretch reflexes do not merely reflect the local stretch of that muscle, and as such, do not act to locally regulate the length of that muscle. Rather, the neural pathway that mediates these reflexes integrates sensory

information from both the elbow and wrist, and even accounts for the arm's orientation, in a manner that supports postural control of the hand — that is, maintaining the hand at its pre-perturbation location. Thus, this spinal feedback pathway can exploit the arm's musculoskeletal redundancy and can implement sophisticated control laws[1] usually considered unique to a transcortical feedback pathway[3].

This is not to say that this spinal feedback pathway can do everything a transcortical feedback pathway can do. Although spinal reflexes are not immutable — modulated by the transition between posture and movement[11], and over the course of several cyclical actions[12], or modified by volitional intent with extensive training[13] — our findings are consistent with many studies showing that the triceps spinal stretch reflex is not modulated by verbal instructions about how to respond to the applied perturbation on a trial-by-trial basis[8]. The functional stretch reflexes we document here are similar in some respects to the withdrawal reflex, wherein a noxious stimulus applied to the skin evokes a spinally mediated response in the muscle that acts to move the skin away from the stimulus[14]. Indeed, the ultimate motor output of both of these spinally generated reflexes are complex and purposeful, and yet are tightly coupled to the sensory input, and do not appear to have the ability to arbitrarily transform sensory feedback into any desired action.

Our results also provide a plausible architecture of the neural pathway that generates the functional stretch reflexes in elbow muscles. This pathway appears to specifically integrate afferent feedback from the triceps (or biceps) and the wrist extensor (or flexor) muscles to functionally tune the triceps (or biceps) stretch reflex to support postural hand control. The presence of heteronymous connections between arm muscles is well established, including wrist and elbow muscles as well as elbow and shoulder muscles[10,15]. Interestingly, the spinal stretch feedback pathway does not appear to always take advantage of such heteronymous connections. For example, previous studies focusing primarily on whole arm reaching have specifically noted that spinal stretch reflexes at the shoulder and elbow respond only to local muscle stretch even when integrating information from the other joint would aid task performance[7,16,17]. Why would heteronymous connections functionally link the elbow and the wrist, but not the
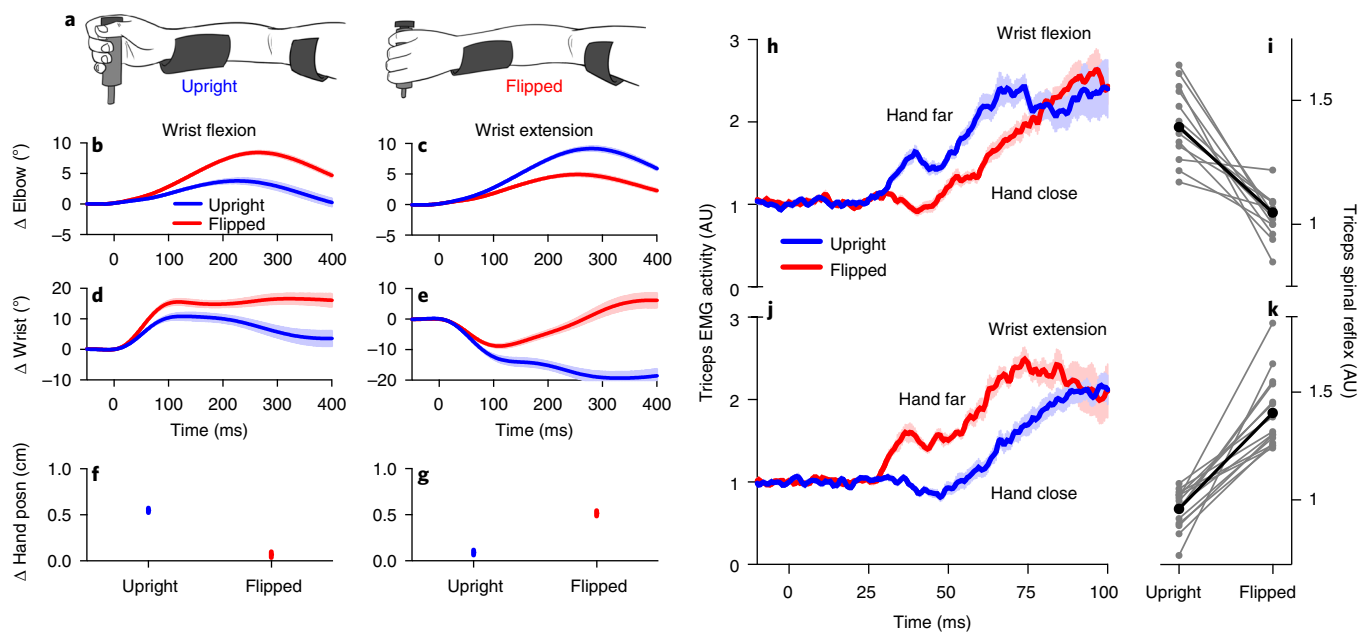
Fig. 3 | Elbow spinal stretch reflex accounts for the arm's orientation. a, Schematic of the upright and flipped orientations. **b**, Mean change in elbow angle following perturbations that flexed the elbow and flexed the wrist. Blue and red traces represent the upright and flipped arm orientations, respectively. Data are aligned to perturbation onset. Shading represents ±1 s.e.m. **c**, Same format as **b** but for perturbations that extended the wrist. **d,e**, Same format as **b** and **c** but for mean change in wrist angle. **f**, 95% confidence interval centred on the group mean hand displacement from the target 20 ms following perturbations that flexed the elbow and flexed the wrist. Blue and red traces reflect the upright and flipped arm orientations, respectively. **g**, Same format as **f** but for perturbations that extended the wrist. **h**, Same format as **b** but for mean rectified triceps EMG activity. **i**, Mean rectified triceps EMG activity in the spinal stretch reflex epoch when the elbow and wrist were flexed as a function of the upright and flipped orientations. Thin grey lines represent individual participants, and the thick black line represents the group mean. **j,k**, Same format as **h** and **i** but for trials in which the elbow was flexed and wrist was extended. All panels represent data from experiment 7 ($n = 15$).

elbow and the shoulder? One possibility is that such differences in neural control arise because of differences in how these joints are anatomically arranged. Unlike the upper arm and forearm, the forearm and hand are usually aligned with one another, meaning that, for keeping the hand stable in a circumscribed part of external space, small disturbances at the wrist can be naturally opposed by counter-rotations at the elbow (akin to how the eyes counter-roll in the head as part of the vestibulo-ocular reflex). The development of a spinal pathway that exploits this anatomical arrangement is beneficial in the context of real-world hand control but may have ultimately arisen as an adaptive mechanism associated with quadrupedal or arboreal locomotion in which similar coordination patterns would be advantageous.

Our findings also reveal that this spinal feedback pathway has a mechanism that tunes the inputs from heteronymous connections such that changing the arm's orientation diametrically alters how the spinal reflex at the elbow integrates information arising from the wrist joint. A similar spinal phenomenon has been documented in the spinalized frog, wherein differences in the limb's initial orientation can influence the trajectories taken to remove a noxious stimulus from the body[18,19]. The non-linear mapping between sensory inputs and motor outputs we report increases the computational capacity of this spinal circuit and seems likely to be implemented via presynaptic inhibition[20], selectively gating which heteronymous inputs act upon the motorneurons that innervate elbow muscles.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41593-019-0336-0.

References
1. Todorov, E. *Nat. Neurosci.* **7**, 907–915 (2004).
2. Cole, K. J., Gracco, V. L. & Abbs, J. H. *Exp. Brain Res.* **56**, 582–585 (1984).
3. Scott, S. H. *Trends Neurosci.* **39**, 512–526 (2016).
4. Cheney, P. D. & Fetz, E. E. *J. Physiol. (Lond.)* **349**, 249–272 (1984).
5. Evarts, E. V. & Tanji, J. *J. Neurophysiol.* **39**, 1069–1080 (1976).
6. Omrani, M., Murnaghan, C. D., Pruszynski, J. A. & Scott, S. H. *eLife* **5**, e13141 (2016).
7. Pruszynski, J. A. et al. *Nature* **478**, 387–390 (2011).
8. Pruszynski, J. A. & Scott, S. H. *Exp. Brain Res.* **218**, 341–359 (2012).
9. Vallbo, A. B. *Acta Physiol. Scand.* **90**, 319–336 (1974).
10. Pierrot-Deseilligny, E. & Burke, D. *The Circuitry of the Human Spinal Cord: Spinal and Cortical Mechanisms of Movement.* 2nd ed. (Cambridge Univ. Press, Cambridge, UK, 2012).
11. Mortimer, J. A., Webster, D. D. & Dukich, T. G. *Brain Res.* **229**, 337–351 (1981).
12. Dufresne, J. R., Soechting, J. F. & Terzuolo, C. A. *Brain Res.* **193**, 67–84 (1980).
13. Thompson, A. K., Chen, X. Y. & Wolpaw, J. R. *J. Neurosci.* **29**, 5784–5792 (2009).
14. Schouenborg, J. Action-based sensory encoding in spinal sensorimotor circuits. *Brain Res. Rev.* **57**, 111–117 (2008).
15. Manning, C. D. & Bawa, P. *J. Neurophysiol.* **106**, 1489–1499 (2011).
16. Kurtzer, I. L., Pruszynski, J. A. & Scott, S. H. *Curr. Biol.* **18**, 449–453 (2008).
17. Soechting, J. F. & Lacquaniti, F. *J. Neurophysiol* **59**, 1296–1313 (1988).
18. Giszter, S. F., McIntyre, J. & Bizzi, E. *J. Neurophysiol.* **62**, 750–767 (1989).
19. Fukson, O. I., Berkinblit, M. B. & Feldman, A. G. *Science* **209**, 1261–1263 (1980).
20. Fink, A. J. et al. *Nature* **509**, 43–48 (2014).

Competing interests

The authors declare no competing interests.

Additional information

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Methods

Participants. A total of 93 individuals (44 males, 49 females; age range 18–34 years) volunteered across seven experiments. All participants reported having no cognitive or motor disabilities, had normal or corrected-to-normal vision and provided informed written consent prior to data collection. This study was approved by the Office of Research Ethics at Western University and was conducted in accordance with the Declaration of Helsinki.

Apparatus. Participants grasped the handle of a three-degrees-of-freedom (shoulder, elbow and wrist) exoskeleton robot (Interactive Motion Technologies: for a depiction of the robot, see ref. [24]). The robot allows for flexion and/or extension of the shoulder, elbow and/or wrist in a horizontal plane, and is equipped with direct-drive motors that generate flexion or extension loads at these joints (torque rise time = 2 ms) and 16-bit rotary encoders (Gurley Precision Instruments) to measure joint angles (resolution = 0.0055 degrees). Visual stimuli were presented downward by a 46-inch LCD monitor (60 Hz, 1,920 × 1,080 pixels, Dynex DX-46L262A12) onto a semi-silvered mirror that occluded vision of the participant's arm. Participants were comfortably seated in a height-adjustable chair and the lights in the experimental suite were extinguished for the duration of data collection.

General experimental procedures. The experimental procedures were similar across our seven experiments. Participants controlled a cursor (turquoise circle, 1 cm diameter) that was mapped to the position of the robot's handle and began each trial by moving the cursor to a start position (red dot, 1 cm diameter) and maintained this position for 500 ms. The robot then gradually applied small loads at the elbow and wrist for 1,500 ms that plateaued at ± 2 Nm and ± 1 Nm (except for experiment 6; see below) at the elbow and wrist, respectively (that is, the pre-loads). The nature (that is, flexion, extension) of these pre-loads differed across the different experiments (see below). A target (red dot, 1 cm diameter) was then presented approximately 5 cm in front of the start position, which corresponded to the position of the cursor when the participant's shoulder, elbow and wrist were at 70°, 60° and 10° of flexion, respectively (external angle coordinate system). When the participant moved the cursor to the target and had their wrist between 5° and 15° of flexion, the target changed from red to green and the start position was extinguished. After participants maintained the cursor at this location with the wrist in the required configuration for 1,000 ms, the cursor was extinguished and the target changed from green to yellow, which served as a perturbation warning cue. Following a randomized foreperiod (1,000–2,500 ms) the robot then applied a 2 Nm step-torque (that is, the perturbation) at the elbow and simultaneously applied a 1 Nm perturbation at the wrist. Mechanical perturbations always flexed the elbow in experiments when a flexion pre-load was applied at the elbow (experiments 1, 3, 4, 6 and 7) and extended the elbow in experiments when an extension pre-load was applied at the elbow (experiments 2 and 5). Wrist perturbations either flexed or extended the wrist randomly on a trial-by-trial basis. Note that in experiments 1, 2 and 3 there was an additional condition in which no wrist perturbation was applied, and that this trial type occurred as frequently and unpredictably as trials when the wrist was mechanically flexed or extended (see Supplementary Fig. 1a–f). The loads associated with the perturbation were quickly removed after 1,300 ms, denoting the end of the trial. The start position then reappeared and participants were required to move the cursor back on this location to initiate a new trial, which enabled them to take rest breaks when desired and kept them engaged in the task throughout the experiment. Participants completed approximately 10 min of practice trials prior to data collection and were told that they could take rest breaks during data collection whenever they wished.

Specific experiment procedures. In experiment 1, participants ($n = 25$; 15 males, 10 females; age range 19–33 years) countered a flexion pre-load at both the elbow and wrist. The perturbation then flexed the elbow and simultaneously either flexed or extended the wrist, or was not applied to the wrist. All participants were instructed to counteract the perturbations and quickly return the cursor to the target. These participants completed 100 trials of each of the three experimental conditions in a randomized order, totalling 300 trials.

In experiment 2, participants ($n = 20$; 7 males, 13 females; age range 19–25 years) countered an extension pre-load at the elbow and wrist. The perturbation then extended the elbow and simultaneously either flexed or extended the wrist, or was not applied to the wrist. Participants were instructed to quickly return the cursor to the target. These participants completed 100 trials of each of the three experimental conditions in a randomized order, totalling 300 trials.

In experiment 3, participants ($n = 15$; 10 males, 5 females; age range 18–27 years) completed two blocks of trials in which they countered a flexion pre-load at both the elbow and wrist. The perturbation then flexed the elbow and simultaneously either flexed or extended the wrist, or was not applied to the wrist. In one block of trials, participants were instructed to quickly return their hand to the target following the perturbation ('counteract') and in the other block were instructed to not intervene following the perturbation ('do not intervene'). Within each block, participants completed 75 trials of the three experimental conditions in a randomized order, totalling 450 trials. The ordering of the

'do not intervene' and the 'counteract' blocks were also randomized across these participants.

In experiment 4, participants ($n = 15$; 8 males, 7 females; age range 18–23 years) countered a flexion pre-load at the elbow and an extension pre-load at the wrist. The perturbation then flexed the elbow and simultaneously either flexed or extended the wrist, and participants were instructed to quickly return the cursor to the target. These participants completed 150 trials of each of the two experimental conditions in a randomized order, totalling 300 trials.

In experiment 5, participants ($n = 20$; 7 males, 13 females; age range 19–24 years) countered an extension pre-load at the elbow and a flexion pre-load at the wrist. The perturbation then extended the elbow and simultaneously either flexed or extended the wrist, and participants were instructed to quickly return the cursor to the target. These participants completed 150 trials of each of the two experimental conditions in a randomized order, totalling 300 trials.

In experiment 6, participants ($n = 15$; 6 males, 9 females; age range 19–23 years) countered a flexion pre-load at the elbow but no pre-load at the wrist. The perturbation then flexed the elbow and simultaneously either flexed or extended the wrist, and participants were instructed to quickly return the cursor to the target. These participants completed 150 trials of each of the two experimental conditions in a randomized order, totalling 300 trials.

In experiment 7, participants ($n = 15$; 9 males, 6 females; age range 19–33 years) completed two blocks of trials in which they countered a flexion pre-load at the elbow and at the wrist. The perturbation then extended the elbow and simultaneously either flexed or extended the wrist. Critically, the blocks in this experiment differed by how the participants physically grasped the robot handle. In one block, participants grasped the handle with their thumb pointing upward (that is, 'upright'), whereas in the other block, participants internally rotated their forearm and grasped the handle with their thumb pointing downward (that is, 'flipped'; see Fig. 3a,b). These different arm orientations dictated how the wrist perturbation moved the cursor relative to the target. For example, perturbations that flexed the wrist moved the cursor away from the target when participants adopted the upright orientation, but moved the cursor towards the target when participants adopted the flipped orientation. Participants completed 75 trials for each of the experimental conditions across both blocks, for a total of 300 trials.

Muscle activity. Participants' skin was cleaned with rubbing alcohol and EMG surface electrode (Delsys Bagnoli-8 system with DE-2.1 sensors) contacts were coated with a conductive gel. The EMG electrodes were then placed on the belly of the lateral head of the triceps brachii, the long head of the biceps, on flexor carpi ulnaris and on extensor carpi radialis after the muscle was manually palpated. Owing to the difficulty of isolating individual wrist muscles with surface EMG, we broadly refer to these wrist muscles as wrist flexors and wrist extensors. A reference electrode was placed on participants' left clavicle. EMG signals were amplified (gain = 1,000), and then digitally sampled at 2,000 Hz.

Data reduction and analysis. EMG data were band-pass filtered (20–250 Hz, 2-pass; second-order Butterworth filter) and full-wave rectified. Muscle activity for each trial was normalized by dividing the muscle's rectified voltage at each time sample by its own mean rectified voltage from the 200 ms window prior to perturbation across all trials (for similar normalization procedures see refs. [21–26]). Only muscles that were activated by the pre-load were analyzed. Angular position of the shoulder, elbow and wrist were sampled at 500 Hz and low-pass filtered (12 Hz, two-pass second-order Butterworth filter).

We compared mean-normalized activity of the triceps spinal stretch reflex and long-latency stretch response, and the biceps spinal stretch reflex, with repeated-measures analysis of variance (ANOVA) or two-sided paired sample t-tests. Post-hoc contrasts were completed with within-subject contrasts (that is, trend analysis) or with two-sided paired sample t-tests. Experimental results were considered reliably different if $p < 0.05$. Partial eta-squared values were computed for effect sizes of repeated-measures ANOVA and within-subject contrasts, whereas Cohen's d was computed for the effect sizes of pair-sample t-tests.

No statistical methods were used to pre-determine sample sizes but our sample sizes are similar to those reported in previous publications [22–25]. Data normality and sphericity (where appropriate) were confirmed with Shapiro–Wilk and Mauchly's tests, respectively. Data collection and analysis were not performed blind to the conditions of the experiments. No data were excluded from analysis. See the Life Sciences Reporting Summary for further details.

Reporting Summary. Further information on experimental design is available in the Nature Research Reporting Summary linked to this article.

Code availability

MATLAB code used for data analyses is available from the corresponding author upon reasonable request.

Data availability

Raw kinematic and EMG data from these experiments are available from the corresponding author upon reasonable request.

References

21. Crevecoeur, F. & Scott, S. H. *PLoS Comput. Biol.* **9**, e1003177 (2013).
22. Crevecoeur, F., Thonnard, J. L., Lefèvre, P.& Scott, S. H. *eNeuro* 3, e0129-15.2016 https://doi.org/10.1523/ENEURO.0129-15.2016 (2016).
23. Pruszynski, J. A., Kurtzer, I. & Scott, S. H. *J. Neurophysiol.* **100**, 224–238 (2008).
24. Weiler, J., Gribble, P. L. & Pruszynski, J. A. *J. Neurophysiol.* **114**, 3242–3254 (2015).
25. Weiler, J., Saravanamuttu, J., Gribble, P. L. & Pruszynski, J. A. *J. Neurophysiol.* **116**, 2236–2249 (2016).
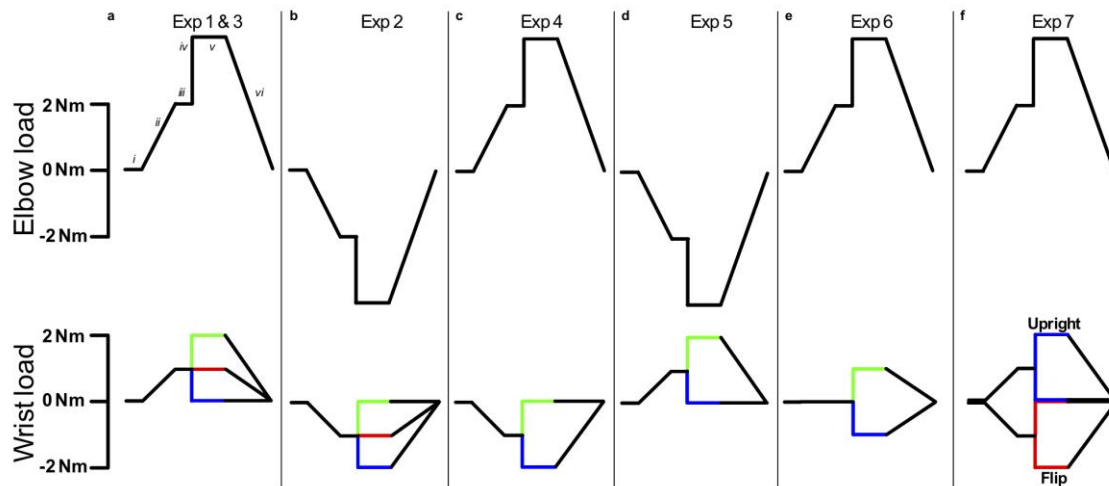26. Yang, L., Michaels, J. A., Pruszynski, J. A. & Scott, S. H. *Exp. Brain Res.* **211**, 231–242 (2011).

Spinal stretch reflexes support efficient hand control

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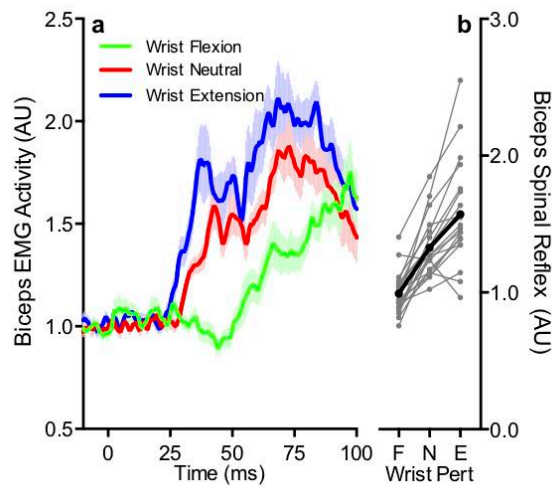[1]Brain and Mind Institute, Western University, London, Ontario, Canada. [2]Department of Psychology, Western University, London, Ontario, Canada. [3]Department of Physiology and Pharmacology, Western University, London, Ontario, Canada. [4]Robarts Research Institute, Western University, London, Ontario, Canada. *e-mail: jeffweilerphd@gmail.com; andrew.pruszynski@uwo.ca

Supplementary Figure 1
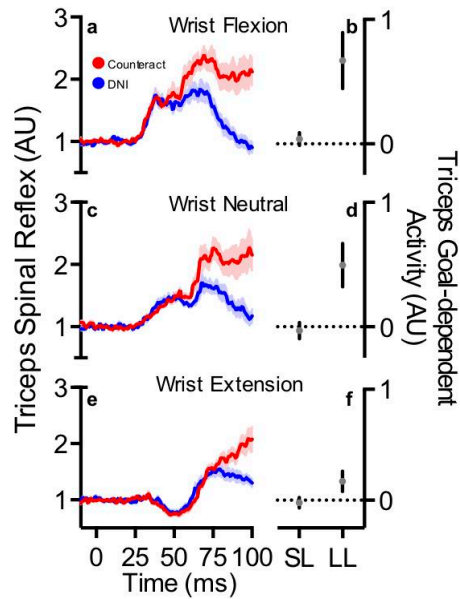
Experimental loads

Mechanical torques (i.e., loads) applied to the elbow (top) and wrist (bottom) across trial-types for each of the seven experiments (a-f). Positive values reflect flexion loads. i: Participants placed their hand to home location for 500 ms. ii: A flexion or extension ramping load was applied at the elbow and wrist over 1500 ms, plateauing at ±2 Nm and ±1 Nm at the elbow and wrist, respectively (the pre-load). iii: Participants moved their hand to a central target and stayed at this location for a randomized foreperiod (2500-3500 ms). iv: A 2 Nm step-torque in the direction of the pre-load was applied at the elbow and a 1 Nm flexion or extension step-torque was simultaneously applied at the wrist (i.e., the perturbation). v: Participants moved the hand back to the target following the perturbation. The load associated with the perturbation remained on for 1300 ms. vi: The loads gradually removed over 1000 ms. Note that the extension pre-load used in the Flip condition of Exp. 7 activates the wrist extensor muscles and that the wrist perturbations across all experiments are colour-coded to correspond with the data presented in all other figures.

Supplementary Figure 2
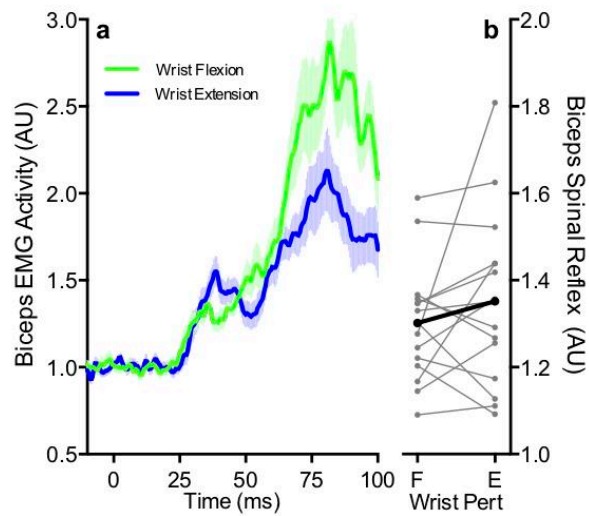
Biceps spinal reflex is tuned to hand displacement

a: Mean rectified biceps EMG activity when the wrist flexor muscles were pre-excited prior to the mechanical perturbation (Experiment 2: n=20). Green and blue traces reflect wrist perturbations that flexed and extended the wrist, respectively, whereas the red trace reflects trials in which no perturbation was applied to the wrist. Data is aligned to perturbation onset. Shading reflects ±1 SEM. **b**: Mean rectified biceps EMG activity in the spinal stretch reflex epoch for the three wrist perturbations (F = flexion; N = none; E = extension). Thin grey lines reflect individual participants and the thick black lines reflect the group mean. The biceps spinal stretch reflex was tuned to the hand's displacement from the target, and not to the amount the elbow was extended, ($F(2,38) = 44.47$, $p < 0.001$, $\eta^2_{partial} = 0.701$; post-hoc trend analysis: linear $F(1,19) = 47.21$, $p < 0.001$, $\eta^2_{partial} = 0.713$; quadratic $F(1,19) = 5.43$, $p = 0.03$, $\eta^2_{partial} = 0.22$).

Supplementary Figure 3

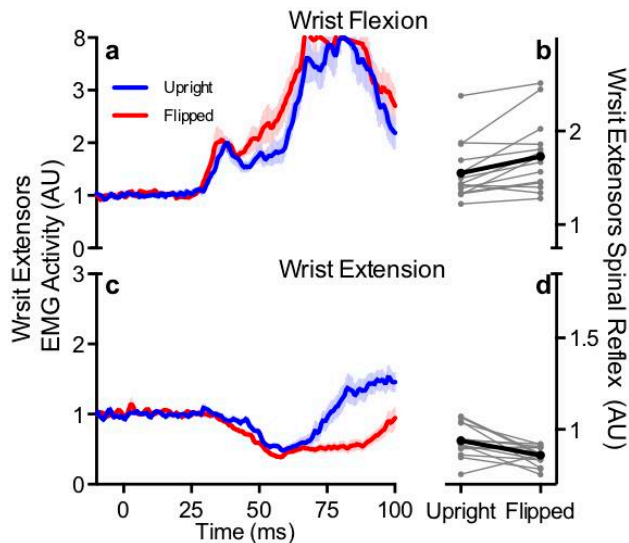**Spinal reflexes are not influenced by volitional intent**

a: Mean rectified triceps EMG activity following the mechanical perturbations that flexed the elbow and flexed the wrist (Experiment 3: n=15). Red and blue traces reflect Counteract and Do Not Intervene blocks, respectively. Data is aligned to perturbation onset. Shading reflects ±1 SEM. **b**: Goal-dependent activity within the spinal (SR) and long-latency (LL) epochs for trials in which the mechanical perturbation flexed the elbow and flexed the wrist. Error bars reflect 95% confidence internals. **c**: Same format as *a*, but for trials where the elbow was flexed and no perturbation was applied to the wrist. **d**: Same format as *b*, but for trials where the elbow was flexed and no perturbation was applied to the wrist. **e**: Same format as *a*, but for trials where the mechanical perturbations flexed the elbow and extended the wrist. **f**: Same format as *b*, but for trials where the mechanical perturbations flexed the elbow and extended the wrist. The magnitude of the triceps spinal stretch reflex was not influenced by the intended action, neither when the wrist was flexed, not perturbed, nor extended (ts(14) all < 1.58, ps all > 0.135, all Cohen *d*s < 0.42). In contrast, the triceps long-latency stretch reflex was influenced by the intended action, and this occurred for all three wrist perturbation conditions (ts(14) all > 4.01, ps all < 0.001, all Cohen *d*s > 1.0: repeated measures ANOVA three-way interaction [epoch (spinal, long-latency) by wrist perturbation (flexed, neutral, extended) by volitional intent (counteract, do not intervene)] for initial omnibus test ($F(2,28) = 17.19$, $p < 0.001$, $\eta^2_{partial} = 0.55$).

Supplementary Figure 4

Determining the source of wrist afferent feedback that tunes the biceps spinal reflex

a: Mean rectified biceps EMG activity when the wrist extensors were pre-excited prior to the mechanical perturbation (Experiment 5: n=20). Green and blue traces reflect wrist perturbations that flexed and extended the wrist, respectively. Data is aligned to perturbation onset. Shading reflects ±1 SEM. **b**: Mean rectified biceps EMG activity in the spinal stretch reflex epoch for when the perturbation flexed (F) or extended (E) the wrist. Thin grey lines reflect individual participants and the thick black line reflects the group mean. The biceps spinal stretch reflex was not influenced but the perturbations applied at the wrist, t(14) = -1.13 p = 0.28, Cohen's d = 0.29, 95%CI [-0.15 -0.05].

Supplementary Figure 5

Wrist muscle activity for the Upright and Flipped orientations

a: Mean rectified wrist extensor EMG activity for perturbations that flexed the elbow and flexed the wrist (Experiment 7: n=15). Blue and red traces reflect the Upright and Flipped arm orientations, respectively. Data aligned to perturbation onset. Shading reflects ±1 SEM. **b**: Mean rectified wrist extensor EMG activity in the spinal stretch reflex epoch when the wrist was flexed as a function of the Upright and Flipped Orientations. Thin grey lines reflect individual participants whereas the thick black line reflects the group mean. **c**: Same format as *a*, but for trials when the wrist was extended. **d**: Same format as *b*, but when the wrist was extended.

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n/a	Confirmed	
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☐	☒	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
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Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	Matlab 2017b was used to record EMG on a computer
Data analysis	Matlab 2017b was used to compute experimental means. SPSS v21 was used for ANOVAs, within-subject contrasts and paired sample t-tests.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors/reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Research guidelines for submitting code & software for further information.

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Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:
- Accession codes, unique identifiers, or web links for publicly available datasets
- A list of figures that have associated raw data
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Raw kinematic and EMG data from these experiments are available from the corresponding author on request.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences   ☒ Behavioural & social sciences   ☐ Ecological, evolutionary & environmental sciences

Behavioural & social sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This was a quantitative study of human movement and muscle activity.
Research sample	A representative sample of young, healthy adults from London, Ontario volunteered for this study. Ages ranged from 18-34, and were comprised of 44 males and 49 females. The sample was selected to determine how the healthy adult nervous system processes sensory feedback to control movement.
Sampling strategy	No statistical methods were used to pre-determine sample size but our sample sizes are similar to those reported in previous publications. Details appear in the Methods section of the manuscript.
Data collection	A robotic exoskeleton connected to a computer was used to collect movement kinematic data. Surface EMG electrodes connected to a computer were used to collect muscle activity data. Only the researcher and the participant were in the experimental suite during data collection. The researcher was not blinded to the experimental conditions or hypotheses being tested.
Timing	Start of data collection: February 2017. End of data collection: July 2018.
Data exclusions	No data were excluded from analysis.
Non-participation	No participants dropped out of the experiment or refused to participate.
Randomization	Participants were not allocated into groups as this was a repeated measures design.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology
☒	☐ Animals and other organisms
☐	☒ Human research participants
☒	☐ Clinical data

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Human research participants

Policy information about studies involving human research participants

Population characteristics	Healthy young adults. Ages ranged from 18 to 34. Comprised of 44 males and 48 females.
Recruitment	Participants were recruited via posted advertisements at Western University and via verbal communication. We do not believe that there was any selection bias. However, any selection bias would not influence our results.
Ethics oversight	Wester University Research Ethics Board

Note that full information on the approval of the study protocol must also be provided in the manuscript.