Separating the control of moving and holding still in post-stroke arm paresis

Alkis M. Hadjiosif[1,2], Kahori Kita[1,3], Scott T. Albert[4,5], Robert A. Scheidt[6], Reza Shadmehr[4], and John W. Krakauer[1,7,8,9]

Abstract

Moving and holding still have been posited to be under separate control regimes for both eye and arm movements. The paretic arm after stroke is notable for abnormalities both at rest and during movement, thus it provides an opportunity to address the relationships between control of reaching, stopping, and stabilizing. In this study, we asked whether independence of these behaviors is preserved in arm paresis. To address this question, we quantified resting postural abnormalities in stroke patients by measuring their biases in force production as they held their hand still in various locations in a planar workspace, and then assessed the influence of these resting force biases on active reaching in the same workspace. We found that patients had marked resting postural force biases at each location, even for the case when arm support was provided. However, these biases did not manifest during any phase of arm-supported planar reaching movements: not during initial acceleration, not to mid-trajectory perturbations, and not during deceleration to a stop. Resting force biases only appeared to switch on after a movement had fully stopped. These findings in stroke suggest that moving and holding still are functionally separable modes of control. At the same time, we found that patients' resting postural force biases mirrored characteristics of abnormal synergies active during movement: they markedly decreased when arm support was provided; they were higher in more distal positions which require breaking out of flexion; and they scaled with the Fugl-Meyer score for the upper extremity (a measure of intrusion of abnormal synergies during active movement). These three shared features suggest a common mechanism for resting postural biases and abnormal synergies, which appears to be a contradiction given the functional separation of moving and holding still observed in the same patients. To resolve this apparent paradox, we propose a model that predicts a breakdown in the functional separation between reaching and holding still when patients move in the absence of weight support. Thus, the model posits that synergies are the behavioral manifestation of a spillover of posture into movement. Mapping these functional systems onto anatomical and physiological details of lesioned substrate after stroke may provide implementation-level insight into how normal arm motor control is assembled.

Author affiliations:

1 Department of Neurology, Johns Hopkins University, Baltimore MD

2 John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge MA

3 Kyoto University School of Medicine, Kyoto Japan

4 Department of Biomedical Engineering, Johns Hopkins University, Baltimore MD

5 University of North Carolina School of Medicine, Chapel Hill NC

6 Department of Biomedical Engineering, Marquette University, Milwaukee WI

7 Department of Neuroscience, Johns Hopkins University, Baltimore MD

8 Department of Physical Medicine and Rehabilitation, Johns Hopkins University, Baltimore MD

9 Santa Fe Institute, Santa Fe, NM

Correspondence to: Alkis Hadjiosif

33 Oxford Street, Suite 319

Cambridge, MA 02138

alkis@seas.harvard.edu alkis@seas.harvard.edu

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Abbreviations: ARAT = Action Research Arm Test; CCW = counter-clockwise; CST = corticospinal tract; CW = clockwise; FM-UE = Fugl-Meyer score for the Upper Extremity; RST = reticulospinal tract

Introduction

A longstanding idea in motor control is that moving and holding still rely upon separate control regimes. This separation was demonstrated in the context of eye movement control by the classic work of David Robinson (Robinson, 1970). Other work suggests this separation may extend to other effectors (Shadmehr, 2017). In particular, substantial behavioral (Ghez et al., 2007) and physiological (Kurtzer et al., 2005; Shalit et al., 2012) evidence supports the idea that a similar dissociation governs the control of reaching and holding still for the arm (Jayasinghe et al., 2022).

Patients with hemiparesis after stroke typically exhibit deficits in the control of both reaching and holding still (Garland et al., 2009; Levin, 1996; Trombly, 1992; Zackowski et al., 2004), making hemiparesis a potent model for understanding the interaction, or dissociation, between these two modes of motor control. There is evidence, for example, that reaching and holding might be differentially affected after stroke depending on lesion side (Mani et al., 2013; Schaefer et al., 2009).

Here, we focused on one particular aspect of holding still: resting at a position. One of the most common and readily recognizable motor symptoms after stroke is abnormal resting posture (Twitchell, 1951). For example, the typical hemiparetic arm posture consists of flexion at the fingers, wrist, and elbow (Carr and Kenney, 1992) (Figure 1A). Prominent approaches for the treatment of hemiparesis have been based on the idea that abnormal resting posture has a direct deleterious effect upon movement control; they advocate for adjusting overall posture in ways that may minimize such effects (Bobath, 1982; Carr and Kenney, 1994, 1992).

Our main aim was to determine whether resting abnormalities bleed over into active movements in the post-stroke arm. This is of great interest because the ability to separate moving from holding may be precisely what is lost after stroke, and hence postural abnormalities could contaminate voluntary movement. If this is indeed the case, it might lend credence to the idea in rehabilitation that treating resting abnormalities can benefit voluntary movement.

In Experiment 1, we assessed resting postural abnormalities by measuring resting postural force biases in patients with stroke using a planar workspace. We investigated how these force biases varied with arm position, presence of arm support, and overall motor impairment. In Experiment 2, we proceeded to assess patients' control of reaching and holding in the same workspace. We separately investigated effects on initial reach and bringing the reach to a stop, as these two might be separately controlled (Ghez et al., 2007; Scheidt and Ghez, 2007).

We also investigated active holding control *after* the movement was over, by examining responses to perturbations that attempted to move the arm off the target, in order to confirm that the same controller is engaged for both passive (as in Experiment 1) and active holding at the same position.

Materials and methods

Participants and Ethics Statement

A convenience sample of 16 stroke patients (age: 58.5±17.8 [average±standard deviation], 9 female) and 9 age-range matched healthy control participants (age: 62.6±15.2, 6 female) were recruited for this study. Table 1 shows details for each patient whereas Table 2 shows summary demographics and assessment metrics for patients and controls. Procedures were approved by the Johns Hopkins Institutional Review Board, and participants provided written informed consent in accordance with the Declaration of Helsinki.

Eligibility criteria

We recruited patients with hemiparesis due to stroke. To be eligible for the study, patients had to be adult, exhibit some movement with the affected arm, and be able to provide informed consent and understand the tasks involved. Exclusion criteria were marked cognitive impairment (assessed based on the Montreal Cognitive Assessment, MoCA, cutoff of 20); severe aphasia or ideomotor apraxia, neglect or hemianopia; and orthopedic or pain issues.

Task Details

Participants were seated on a chair and grasped the handle of a robotic arm; the handle moved either passively (by itself, Experiment 1) or actively (by the participant, Experiment 2) on the horizontal plane. In Experiment 2 and in two out of four conditions of Experiment 1, participants' lower arm was supported using a custom-made air-sled (Figure 1C). Above the plane was a screen which blocked direct vision of the arm; on this opaque screen we continuously projected a cursor indicating hand position (diameter: 3 mm), as well as the currently active target (diameter: 10 mm). Handle position was recorded at 200Hz, whereas subject-produced forces on the handle were recorder using a 6-axis force transducer. Experiments typically began with the paretic arm (see specific details below); for healthy controls, an arm was randomly assigned as primary, with its schedule matching that of the paretic arm in stroke patients.

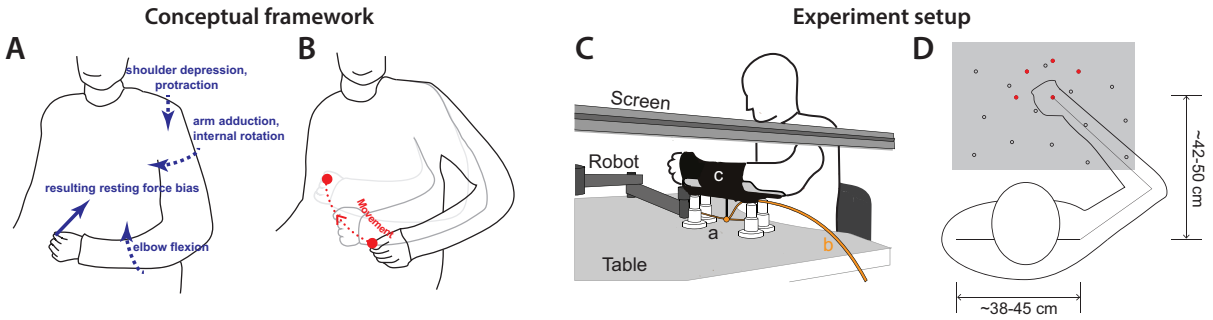


Figure 1: Framework and experiment setup. *(**A**) A patient exhibiting a typical flexor posture at rest. Dashed arrows indicate elements of the posture: shoulder depression, arm adduction/internal rotation, elbow flexion. The torques involved in each component of the abnormal resting posture translate to a force on the hand (blue arrow); we thus designed an experiment to measure the resting force bias on the hand, as a marker of the overall postural abnormality. The goal was to compare resting postural force biases to active movement control in the same area (**B**). (**C**) Experiment setup. The participant holds the handle of the robotic arm; reach targets and cursor position are projected on a screen on top; for arm support, the participant's arm is strapped on an armrest (**c**) connected to an air sled (**a**) which rests on the table. Air is provided through tube labeled (**b**). (**D**) Top-down view of setup, illustrating the different hand positions where resting postural forces were measured in Experiment 1 (open circles). Also shown are the five target positions used in the reaching and holding task for Experiment 2 (filled red circles). The gray box indicates the workspace depicted in Figure 2.*

Experiment 1: Measuring resting postural abnormalities

Following a previous paradigm (Kanade-Mehta et al., 2022; Laczko et al., 2017; Simo et al., 2013), Experiment 1 assessed resting postural forces by passively moving participants to different positions in a 2D workspace and holding them still in each position while it measured the forces they inadvertently exerted. Participants were instructed to maintain grasp on the robotic handle but otherwise rest and not resist the robot's motion as it slowly (5s movement time) moved from one position to the next and held them still (for an additional 5s). The array of positions (see Figure 1) could vary from one participant to the next, with each position visited three times for each block. During the passive moving and holding, a 3 mm white cursor indicating handle position and a 10 mm yellow disk indicating the destination of the passive movement were displayed. Though not essential from the participant's point of view, this allowed the experimenter to monitor the status of the experiment.

Each participant completed 4 blocks, two with each arm and in each arm support condition (air sled, no air sled); the typical order was {paretic, no support} -> {non-paretic, no support} -> {paretic, air sled support} -> {non-paretic, air sled support}; however in four individuals we completed the two paretic blocks first as their hand had to be secured to the handle (with self-adherent wrap) for a stable grasp.

Each block typically took less than 10 minutes to complete, with Experiment 1 lasting about 40 minutes including breaks.

Experiment 2: Assessing reaching control

Using the same workspace as Experiment 1, Experiment 2 assessed motor control in a reaching task. Participants made 10-cm point-to-point reaches across an array of 5 targets (diameter: 10mm) within the workspace (Figure 3A), sampling 8 different movement directions. A white cursor (diameter: 3mm), indicating hand position, was visible throughout the experiment. Participants were instructed to try and stop at each target within a 600-800ms window after movement onset. At the end of movement, feedback was provided to indicate whether they were too fast (time <600ms, target turning red), too slow (time>800ms, target turning blue), or within the right time range (target “exploding” with a chirping sound).

The experiment was divided into blocks of 96 movements each (12 in each of the 8 movement directions). It began with three blocks with the paretic arm, followed by three more with the non-paretic arm, two more with the paretic arm, and ending with two blocks with the non-paretic arm. The first block with each arm was a familiarization block. Arm support (air sled) was provided throughout the experiment, and breaks were given between blocks.

Except for two participants, who performed Experiment 1 and Experiment 2 on different days due to limitations in their schedule, the entirety of each session – consisting of Experiment 1, Experiment 2 and standard assessments - took place on the same day and typically lasted about 3.5 hours with breaks given between the blocks as necessary.

Most trials (two-thirds) consisted of unperturbed movements to assess reaching control. In the remaining third of reaches, a 12N, 70 ms bell-shaped force pulse was applied by the robot lateral to the movement direction (Smith and Shadmehr, 2005) after participants reached 2cm away from the starting position. On half of these trials the perturbation was oriented leftwards with respect to the movement (counterclockwise pulse) and the other half rightwards (clockwise pulse).

A fraction of trials in each block (20/96) imposed a static perturbation after movement in order to assess active holding control. For these trials, the holding time at the target was extended by 5 to 7 seconds, during which participants were instructed to hold still on the target (to remind them, the word “HOLD” were shown close to the target). During this extended hold period, a 6N force was gradually imposed over 2s in one of four different directions (45˚, 135˚, 225˚, 315˚), held constant for a pseudorandom time interval uniformly ranging from 3 to 5 seconds,

and then abruptly released. Each block presented each position/static perturbation direction combination exactly once.

Data Analysis

Analysis was performed using MATLAB (Mathworks, Natick MA). For Experiment 1, we averaged resting postural forces for the last 3s of the 5s passive holding period for each trial. We excluded the first 2s in order to avoid measuring potential increases in muscle tone that may arise due to the velocity by which the robot passively brought the arm to each measurement position (i.e., avoiding potential effects of spasticity). Recent work using a similar task to examine resting force biases, found that the effects of the velocity at which the robot brought the arm to a position are present for 2s after the end of the passive movement, but then dissipate (Kanade-Mehta et al., 2022). To obtain a measure of the average resting postural force at each position for each individual and condition, we further averaged forces across the three visits to the same position. For comparisons, we focused on resting postural forces on the 5 positions shown in Figure 1E; these forces were obtained directly (when the exact positions were sampled for the individual) or through interpolation (7/16 patients and 3/9 controls).

For Experiment 2, movement onset was defined as the moment in which participants' velocity from the starting position exceeded 3.5 cm/s, movement end was defined as the moment the participant was within the target and moving at a speed of less than 3.5 cm/s. Initial reaching angle was calculated between hand position at movement onset and 150ms later; endpoint reaching angle was calculated between the position of the hand when it crossed within 2cm of the target and 150ms later. In pulse trials, settling time was defined as the time taken from pulse onset to the first moment absolute lateral velocity dipped below 2cm/s and remained so for at least 100ms (or the movement ended). In static perturbation trials, settling time was defined as the time taken from perturbation onset (release of holding force) to the moment when velocity dipped below 2cm/s (and remained below that amount for at least 100ms) and the distance from the target was less than 2cm.

Data exclusion criteria

In Experiment 1, some trials (7.5%) were flagged as erroneous after visual inspection of force profiles. Erroneous here refers to trials where forces appeared unstable and/or there was movement during the robot hold period. We excluded these trials from our main analyses. To ensure that this exclusion did not bias our findings, we repeated our analyses including these trials and obtained similar results.

In Experiment 2, we excluded as outliers movements in which initial movement direction (150ms after movement onset) was ≥90° away from target direction. This excluded 0.95% of patients' movements and 0.33% of controls' movements.

Moreover, in some static perturbation trials, patients took a long time to reach the stabilization criterion described in the previous section; mistakenly, our setup limited its recording time to only the first 2s after force release. The exact time to stabilization thus could not be measured for these particular trials, so they had to be excluded from analysis. Though only 13.2±3.3% (mean±SEM) of paretic stabilization trials were thus excluded in the patient population (1.4±0.4% in their non-paretic side, 2.3±2.0% in controls), there were three patients for which excluded trials were 25% or more of all paretic trials. To ensure there are no systematic effects of this issue, we repeated the analysis of Figure 7F (a) by excluding these four patients altogether or (b) by assigning a value of 2.0 seconds to the affected trials. In both cases, we obtained results similar to our main analysis (Figure S1).

Statistical comparisons

In Experiment 1, we used an ANOVA to investigate any effect of conditions {Position (distal/proximal), Support (with/without air sled), FM-UE (continuous)} and their interactions. We used paired t-tests for the within-subject comparisons in Experiment 2.

Fugl-Meyer assessments

Assessments were separately scored by AMH and KK with scores subsequently averaged (hence some scores having decimal values). For cases of substantial score differences (3 points or more) scores were again reviewed by both raters together.

Results

Patients showed resting flexor biases across the workspace

We first assessed post-stroke resting postural abnormalities across a 2D workspace. In Experiment 1, participants grasped the handle of a robotic arm, which passively moved their hand to a series of positions that sampled the workspace in front of them (the setup and example workspace are shown in Figure 1C,D). Participants were instructed to maintain grasp, but otherwise relax their arm and not resist the actions of the robotic arm. Once the participant's arm was passively moved to a given position, the robotic arm would hold still for 5 seconds, enabling us to measure the forces involuntarily exerted by the participant as their hand was held at that location. Each experimental block consisted of three visits to 15-25 positions sampled for each participant, in random order. Participants completed four different experiment blocks: two with each arm, with or without arm weight support (provided by an air sled, Figure 1C).

Patients displayed abnormal postural force biases when the robot held the hand still at various locations across the workspace. Figure 2 shows examples of this for three patients and a typical healthy control participant. The non-paretic arm produced little to no postural force biases, whereas the paretic arm produced substantial postural force biases, particularly when the hand was held in a more distal position. The postural force biases were strongest when patients had to support the weight of the arm against gravity. Moreover, the patient with the highest degree of impairment (top left subplot of Figure 2, as assessed using the Fugl-Meyer score for the Upper Extremity, FM-UE (Fugl-Meyer et al., 1975)) exhibited the strongest resting postural abnormalities.

To aggregate results across all participants, we focused on abnormal resting postural force biases at five specific hand locations, illustrated by the red dots in Figure 2. These locations were chosen as they were within the sampled workspace of all participants (as this workspace could differ from one participant to the next due to different participants' segment lengths), contained both distal and proximal targets, and, importantly, they were also the movement targets used in Experiment 2. Figure 3A shows subject-averaged resting postural forces at each of these five positions and Figure 3B shows the corresponding force magnitudes averaged across subjects and the five positions. There were two key observations: first, postural force biases were stronger in locations further away from the body and tended to point towards it; second, postural force biases were roughly halved in magnitude when arm support was provided.

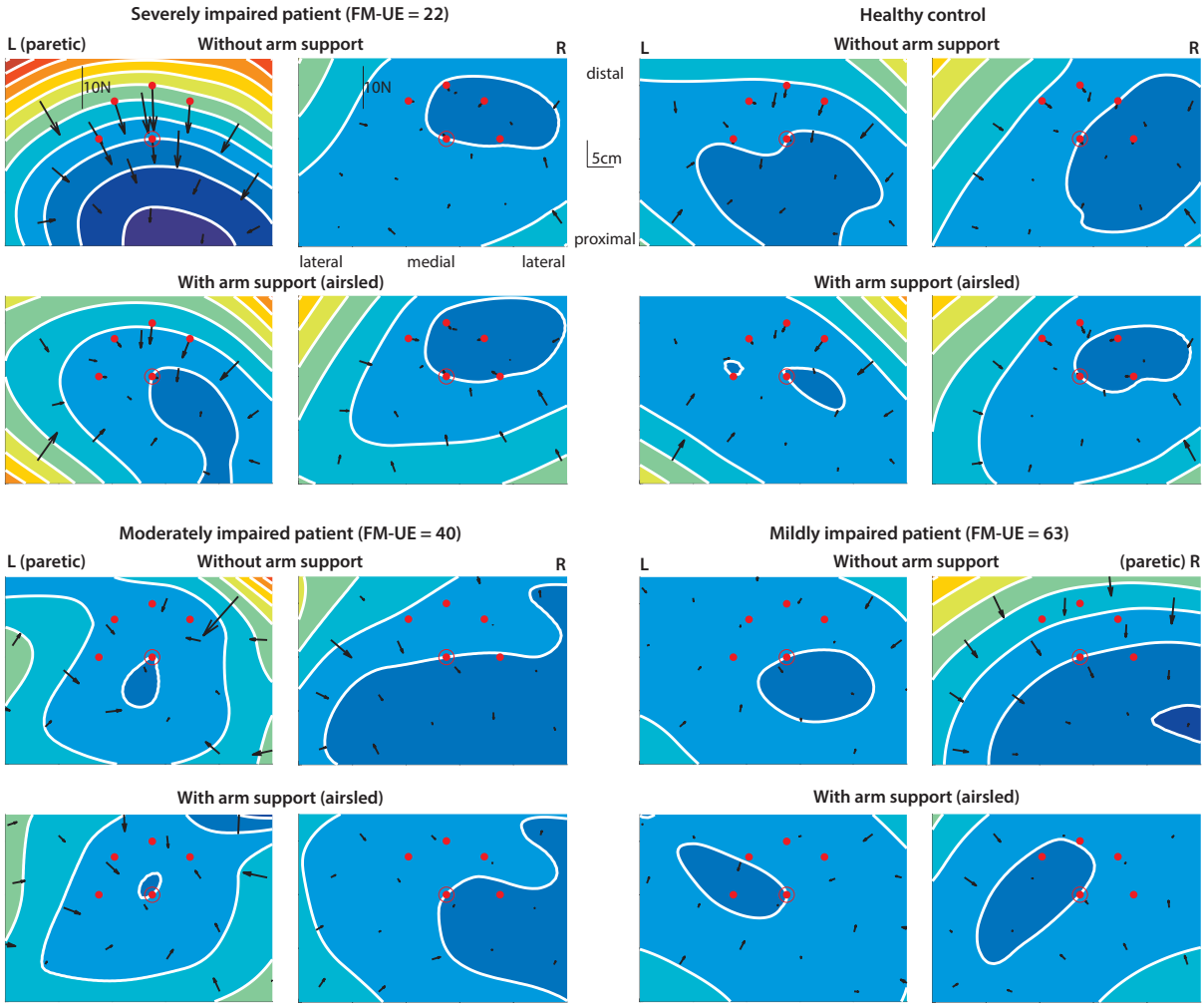
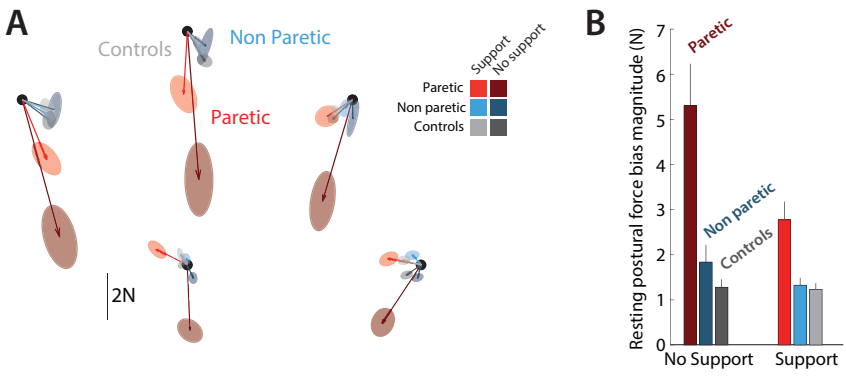


Figure 2: Examples of resting postural force biases. *Shown are three stroke patients and one healthy control. Arrows indicate magnitude and direction of abnormal resting postural forces as measured at the hand at each location. Isoclines indicate gradations in force magnitude; different colors indicate different force levels based on these gradations. The red dots are the reach targets, with the center location circled (used in Experiment 2). Note how abnormalities in the paretic side are considerably stronger when arm support is removed. FM-UE: Fugl-Meyer score for the Upper Extremity (0-66).*

Resting postural force biases did not affect the control of active reaching in the same workspace

In Experiment 2, we sought to investigate whether resting postural force biases influence active reaching and holding still in the same workspace. We measured effects upon the initial reach (Figure 4, blue) and bringing the reach to a stop (Figure 4, red), as it has been suggested that these two components are separately controlled (Ghez et al., 2007; Scheidt and Ghez, 2007); see also (Karst and Hasan, 1991; Lestienne, 1979). We also asked whether the same



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286 ***Figure 3: Average resting postural force biases.*** *(**A**) Average resting postural forces for the paretic*
287 *(red) and non-paretic (cyan) arms of patients, as well as control participants (gray), illustrating how*
288 *abnormal forces in the paretic arm are stronger in more distal targets and attenuated when arm support*
289 *is provided (lighter shades). To average across left- and right-hemiparetic patients, left-arm forces were*
290 *flipped left to right. (**B**) corresponding average resting postural force magnitudes.*

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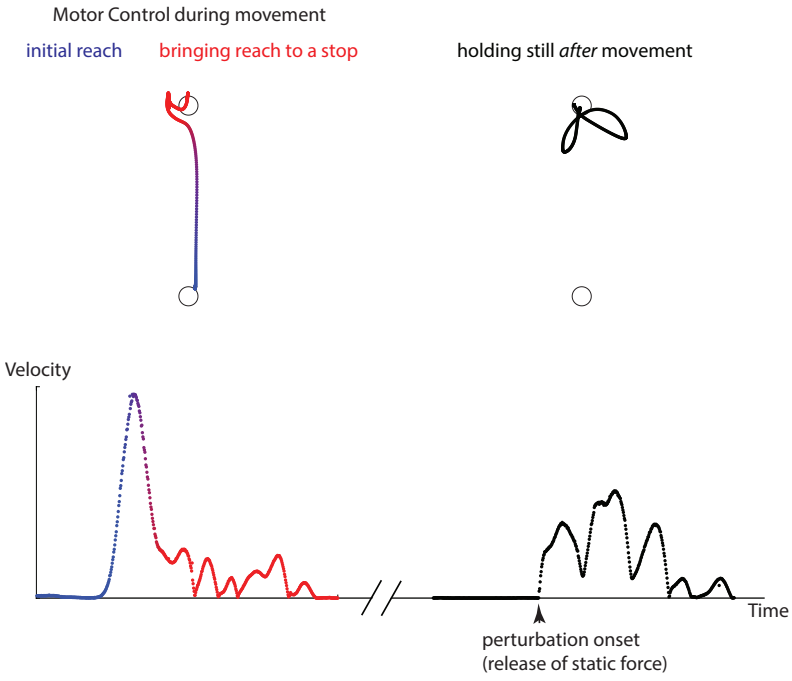

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293 ***Figure 4 Three aspects of active motor control that we tested in Experiment 2.*** *We separately*
294 *examined the early part of the reaching movement (blue) and the late part, when the arm was coming*
295 *to a stop (red). This was done by studying both unperturbed movements at different stages and*
296 *movements that were perturbed with brief force pulses. In addition, we examined active holding control*
297 *after the movement was over (black), using perturbations that tried to move the arm away from the held*
298 *point. Shown is an example of trajectory and (absolute) velocity profiles from the reaching and coming-*
299 *to-a-stop parts of a trial (left) and active holding against a perturbation after the trial was over (right).*

300

controller is engaged while the arm is passively held at a position (as in Experiment 1) vs. actively held at the same position. For this purpose, we examined active holding control *after* the movement was over (Figure 4, black), using perturbations that attempted to push the arm off the target.

We began by examining the control of active reaching. Participants made 10-cm point-to-point reaching movements within an array of five positions (filled circles in Figure 1D), for a total of 8 different movement directions (Figure 5A). Arm support was provided by the air sled (Figure 1C). Patients' movements were generally impaired, taking more time and traveling a longer path to reach the target than controls (Time to target: 1.59±0.12s for patients' paretic side vs. 0.82±0.03s for controls, $p = 0.00006$; Path traveled to target 13.4±0.6cm for patients' paretic side vs. 10.8±0.2cm for controls, $p = 0.007$, Fig. 5B,C).

We then examined whether patients' movements were affected by the resting postural biases measured in Experiment 1 in the same workspace and under the same arm-support condition. Would there, for example, be a difference when moving the arm through a high-postural bias area vs. a low-postural bias area? We examined effects of resting postural biases upon the initial reach vs. the approach to a hold position, as separate mechanisms may be involved in the control of each phase of movement (Ghez et al., 2007; Hannaford and Stark, 1985; Karst and Hasan, 1991; Sainburg et al., 1999; Scheidt and Ghez, 2007); resting postural biases might affect one phase but not the other. Specifically, we examined: (a) whether the direction of resting postural forces at the start position influenced trajectory deviations near the beginning of the movement (Figure 5D) or (b) whether direction of resting postural forces at the end position influenced trajectory deviations near the end of the movement (Figure 5G, after the participant reached within 2cm of the target).

To investigate within-subject effects, we selected, for each participant, the two movement directions for which the corresponding postural forces had strongest opposing effects – i.e. the most rightwards (CW) vs. most leftwards (CCW) with respect to movement direction. The idea behind picking the most extreme values for each individual was to maximize our sensitivity in detecting potential effects of resting postural forces upon active movement. Our analysis found no significant differences in directional biases between these two conditions: while the selected start-point force biases differed considerably between the most CCW and CW cases (1.9±0.4N vs. -2.1±0.4N, correspondingly [negative signs indicating CW forces], $t_{15}=5.68$, $p=0.00004$), the corresponding initial angular deviations did not (0.4±2.1˚ for the most CCW vs. -1.6±2.2˚ for the most CW postural force, $t_{15}=0.56$, $p=0.58$, Figure 5D-F). Similarly, while the selected end-point force biases also differed considerably (2.1±0.4N vs. -1.9±0.4N, for the most CCW vs. CW cases, $t_{15}=5.68$, $p=0.00004$), the corresponding endpoint angular

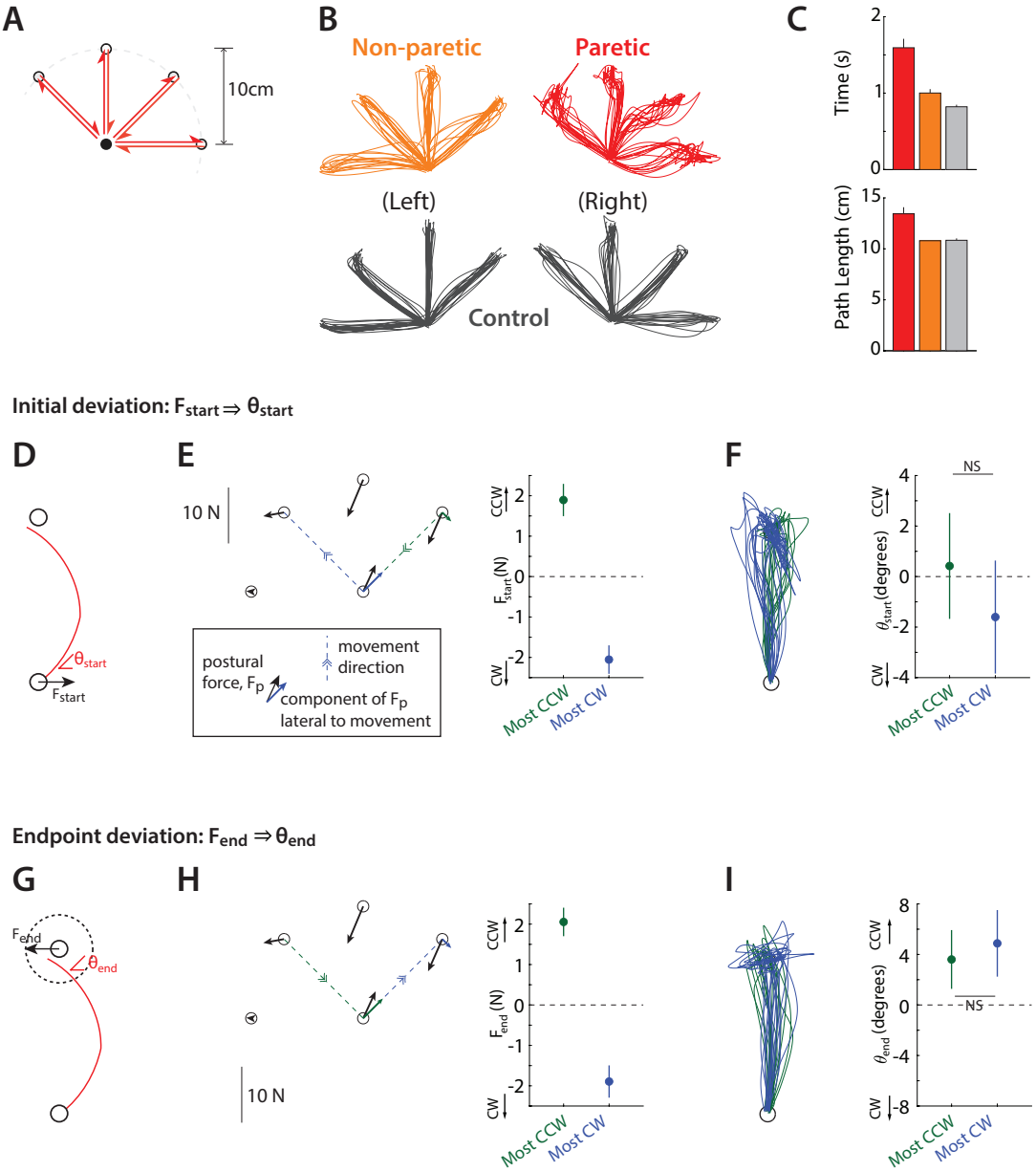

Figure 5: Abnormal resting postural force biases do not interact with active reaching. ***(A)*** *Target array for Experiment 2 (movement task), illustrating the 5 start/end points of reaches and the 8 movement directions. (**B**) Example outwards trajectories (unperturbed trials) for a patient (orange: non-paretic side; red: paretic side) and a healthy control (gray). (**C**) Subject-averaged reach performance based on either time (top) or path length to target (bottom) indicates impaired reaching control in patients' paretic side. (**D-F**) Within-subject analysis of whether resting postural forces at movement start bias early movement towards their direction. (**E**) For each individual, we selected the direction where F_{start} was the strongest counterclockwise (CCW, green) or clockwise (CW, blue). The left panel shows this selection for an example participant: postural forces at start position were projected lateral to the movement direction, allowing us to select movement directions for which this component was directed the strongest CCW or CW. The right panel shows the magnitude of these selected components across all patients. (**F**) Left: Corresponding movement trajectories (rotated so start position is at the bottom*

*and end position at the top) for the directions selected for the same example participant. Right: Average initial angular deviations, θ_{start}, for the selected directions for each participant, revealing no difference and thus no effect of F_{start} upon the movement. (**G-I)** same as D-F but for endpoint resting postural forces, F_{end} and endpoint deviations, θ_{end}. Errorbars indicate SEM.*

deviations did not (3.6±2.3˚ for the most CCW vs. 4.9±2.6˚ for the most CW postural force, t_{15}=0.50, p=0.62, Figure 5G-I). In summary, our data provide no compelling evidence that postural abnormalities directly affect active movement.

Resting postural force biases did not affect responses to perturbations during active reaching

A potential limitation in our data and analysis above is that unperturbed reaching movements may provide limited sensitivity in detecting effects of resting postural force biases, as any such effects may be largely compensated by a predetermined motor plan. In that case, it may be better to directly compare these force biases to responses to less predictable, externally applied force perturbations. We thus further assessed how resting postural forces may affect responses to mid-movement perturbations. In 1/3 of randomly selected reaching movements in Experiment 2, we imposed a 70ms duration, 12-N force pulse lateral to the movement (Smith and Shadmehr, 2005) 2cm into the reach. Half of these pulses were clockwise (CW, blue in Figure 6A) and the other half were counter-clockwise (CCW, red in Figure 6A). We first verified that these pulses had a clear effect upon movement: perturbed movements took longer to complete in both patients (paretic movement time: 1.72±0.13s vs. 1.59±0.12s, t_{15} =5.31, p = 0.00009) and controls (movement time: 0.88±0.03s vs. 0.82±0.03s, t_8 =5.56, p = 0.0005). Patients generally had impaired response to these pulses compared to their non-paretic side and healthy controls, deviating further (maximum lateral deviation – paretic: 2.5±0.1cm vs. non-paretic: 2.1±0.1cm [p= 0.0008] and controls: 2.1±0.1cm [p = 0.0244] - average of CW and CCW pulses) and taking a longer time to stabilize in the pulse direction (i.e. settling time; paretic: 1.15±0.06s vs. non-paretic: 0.76±0.03s [p=0.00002] and controls: 0.74±0.02s [p = 0.00002]). This is illustrated in Figure 6B,C.

We then investigated whether resting postural forces played any role in patients' response to the pulse perturbation. We hypothesized that, should resting postural forces play a role, they would tend to reduce the effect of the pulse if they were in the opposite direction, and exaggerate it they were in the same direction. We thus compared the lateral component of resting postural forces in the start position against (a) the maximum lateral deviation in the

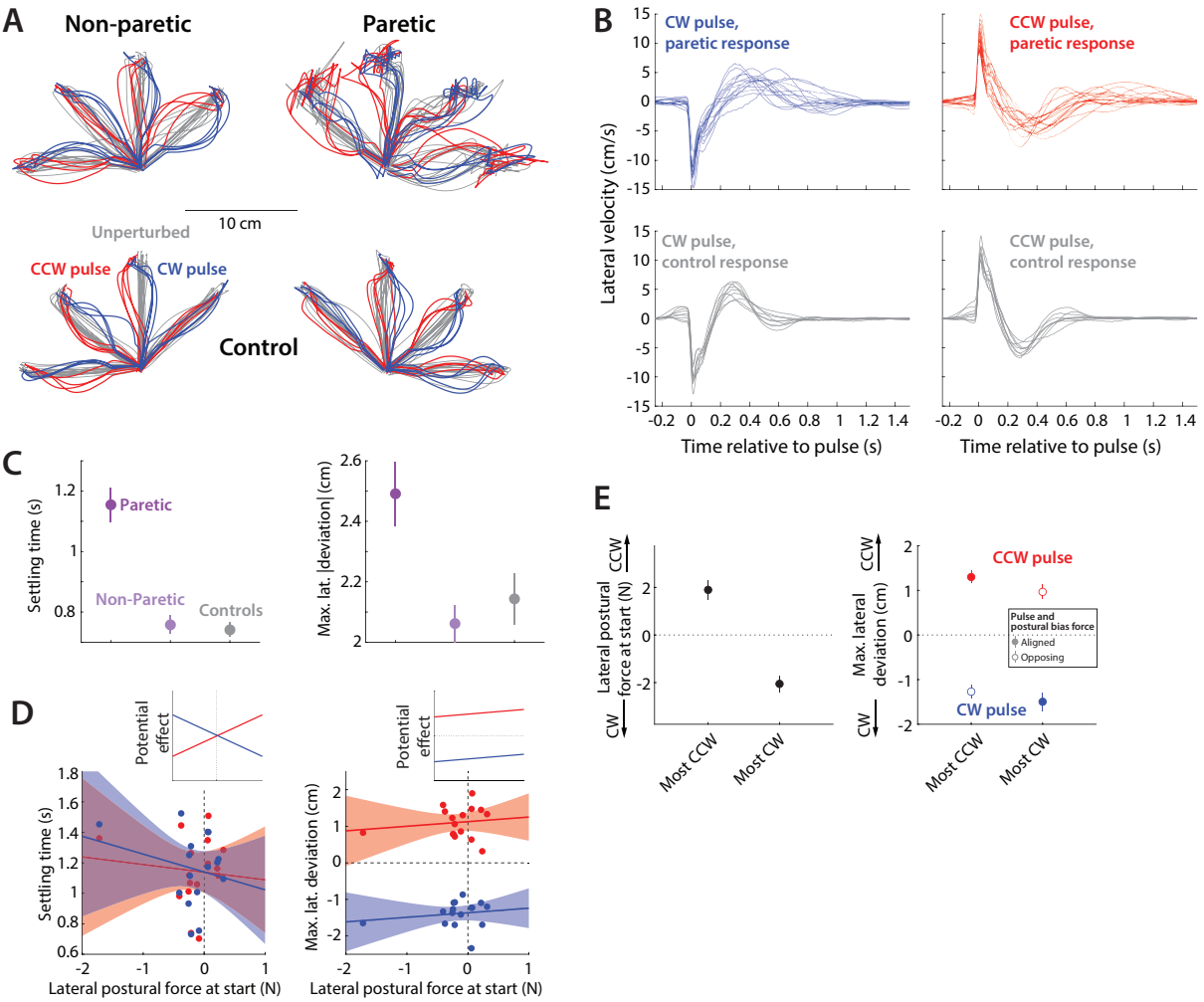

Figure 6: Responses to movement perturbations are not affected by resting postural force biases. (A) *Examples of perturbed (red: perturbed with CCW pulse; blue: perturbed with CW pulse) and unperturbed (gray) outward trajectories - same individuals as in Figure 3B. (**B**) Lateral velocity (positive: CCW to movement) before and after pulse onset, and corresponding responses from controls (gray), illustrating how patients, in response to the pulse, take longer time to settle and tend to experience larger lateral deviations compared to controls. (**C**) Summary performance measures for patients and controls, indicating impaired performance with the paretic side: settling time (left) and maximum lateral deviation on pulse direction (right). (**D**) Left: Across-patient comparison between settling time and lateral postural bias force on movement start. Inset indicates expected relationships if resting postural biases were affecting the response against the pulse. Paretic data shown. Red: CCW pulse; Blue: CW pulse. Right: similar to left, but for (signed) maximum lateral deviation for the two types of pulses. (**E**) Within-individual analysis: here, for each individual, we selected the movements for which the starting-position resting postural force would be either the strongest CCW or CW (left); we then examined the corresponding maximum lateral deviations (right). Mirroring the analysis shown in D, any potential effects of the most CCW vs. most CW resting postural forces are inconsistent: in one case there is a tendency for increased deviation when the resting postural force is aligned with (filled circles) instead of opposing (open circles) the pulse, and in the other case it is the other way round.*

direction of each pulse and (b) the time taken to stabilize in the pulse direction (settling time). When we compared force magnitude vs. maximum lateral deviation in pulse direction we found no relationship for either CCW pulses (R^2=0.02, p = 0.61) or CW pulses (R^2=0.03, p = 0.54) as shown in Figure 6D, right. Similarly, we found no relationship when comparing force magnitude vs. settling time (CCW pulses: R^2=0.01, p = 0.70, CW pulses: R^2=0.05, p = 0.39, Figure 6D, left). In summary, our analysis did not show any consistent systematic effects of resting posture upon the responses to pulse perturbations.

However, this across-subject analysis may mask within-subject differences. Thus, in a manner similar to the previous section, we selected, for each individual, the directions where the starting lateral postural force was most CCW vs. most CW, and compared the corresponding deviations. We found no clear effect: when resting postural forces were the most opposed to the pulse (vs. most aligned with it) there were no clear differences in deviation along the pulse direction, for neither the CCW pulses (0.97±0.17 vs. 1.30±0.14cm, t_{15} = 1.48, p = 0.16), the CW pulses (1.27±0.16 vs.1.50±0.20cm, t_{15} =0.87, p = 0.40), or with both types of pulses pooled together (1.12±0.12 vs. 1.40±0.11cm, t_{15} =1.42, p = 0.18). In summary, we found no evidence for an interaction between resting postural force biases and the ability to respond to perturbations that were applied during movement.

Resting postural force biases emerged during active holding at the end of movement

Finally, in Experiment 2, we also investigated the relationship between resting postural force biases and active holding. In 20 out of 96 movements in each block, participants had to hold steady on the target for an additional 5 to 7 seconds (Figure 7A). During this time, the robot imposed a 6N force in one of four directions (45˚, 135˚, 225˚, 315˚, as shown in Figure 7B). This force was gradually applied over two seconds, held at a 6N level for 3-5 seconds, and then abruptly released, acting to displace the arm in the direction opposite to the original force, as illustrated in the examples in Figure 7B.

Patients showed impaired capacity to resist and recover from this perturbation (the abrupt release of the imposed force), taking a longer time (0.94±0.05s for the paretic side vs. 0.79±0.03s for the non-paretic side [p = 0.024] and 0.78±0.06s for controls [p = 0.061], Figure 7E, left) and traveling a longer path (7.7±0.7cm for the paretic side vs. 5.9±0.3cm for the non-paretic side [p = 0.012] and 5.4±0.5cm for controls [p = 0.026], Figure 7E, middle) to stabilization; moreover, they deviated more in the direction of the perturbation (3.3±0.2cm for

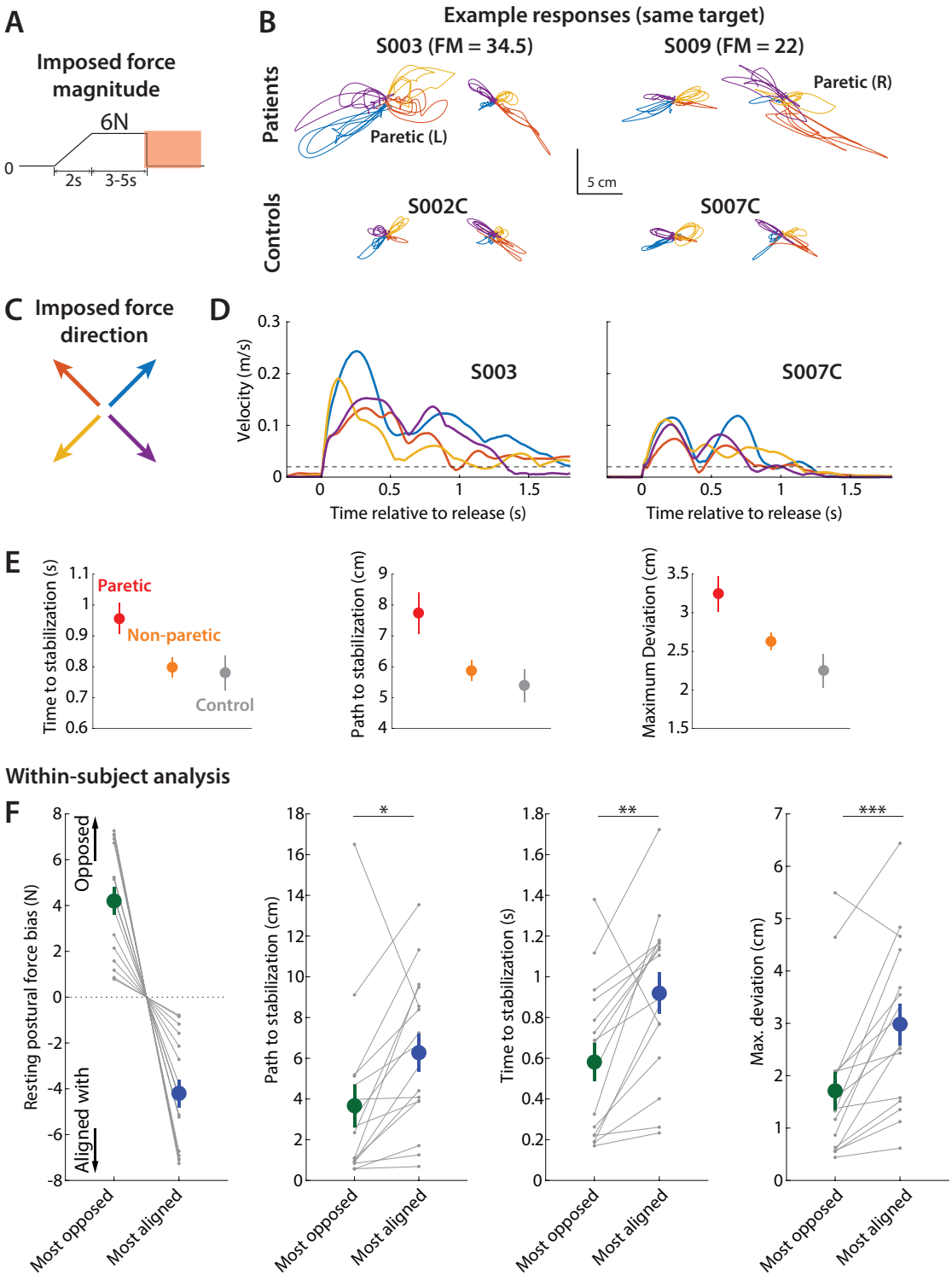

Figure 7: Responses to static perturbations and their relationship to resting postural forces. *(**A**) Time course of the perturbation. (**B**) Example responses (all for the same position in the workspace) from two patients (top row) and two controls (bottom row). (**C**) Corresponding imposed force directions, the abrupt removal of which perturbs the movement in the opposite direction (compare with B). (**D**) Examples of tangential velocity profiles after the sudden release to the imposed hand force, averaged for all trials at the same position for each participant. Dashed line indicates the 2cm/s threshold used to*

*assess time to stabilize. Left; example patient (paretic side); Right; example control. Colors correspond to different directions of the imposed hand force. (**E**) Summary of performance metrics after the perturbation for the paretic and non-paretic side of patients and healthy controls. (**F**) Within-subject analysis of the relationship between resting postural forces in the direction of the perturbation vs. performance against the perturbation. For each individual, we selected the two position/perturbation direction combinations for which resting postural forces were either the most opposed (green) to the perturbation or the most aligned (blue) with it. From left to right: forces in selected position/perturbation direction combinations; corresponding path traveled to stabilization; corresponding time to stabilization; corresponding maximum deviation. This analysis suggests that restoring hand position after the perturbation is indeed easier when resting postural forces opposed, rather than were aligned with, the perturbation. Gray dots indicate individual data; colored dots and errorbars indicate mean±SEM.*

the paretic side vs. 2.6±0.1cm for the non-paretic side [p = 0.012] and 2.3±0.2 for controls [p = 0.0078], Figure 7E, right).

To investigate whether resting postural force biases affected the control of actively holding still across workspace locations, we performed a within-individual analysis analogous to the one we used for unperturbed reaches and moving perturbations. We first projected resting postural forces upon the directions of the static perturbation to assess the component of the resting postural force that opposed or aligned with the static perturbation. We then selected, for each participant, the two position/perturbation direction combinations for which these forces were either the most opposed (Figure 7F, green) to the perturbation or the most aligned (Figure 7F, blue) with it. For these selected position/perturbation direction combinations, we compared capacity to resist and recover from the perturbation, and found that this capacity was indeed better when the resting postural force was in a direction that opposed the perturbation (path traveled to stabilization: 3.7±1.0cm vs. 6.3±0.9cm, t_{15}=2.8, p=0.014; time to stabilization: 0.6±0.1s vs. 0.9±0.1s, t_{15}=3.8, p = 0.0017; maximum deviation: 1.7±0.4cm vs. 3.0±0.4cm, t_{15}=4.6, p = 0.00036, corresponding to cases with the most opposed vs. the most aligned resting postural force). In short, our perturbations revealed that resting flexor biases switched on after movement was over, providing evidence for separate control between moving and holding still.

Relating resting postural force biases to the Fugl-Meyer scale for the Upper Extremity

The observation, from Experiment 1, that resting postural force biases are reduced by external arm support bears parallels to the same effect of arm support upon abnormal synergies active

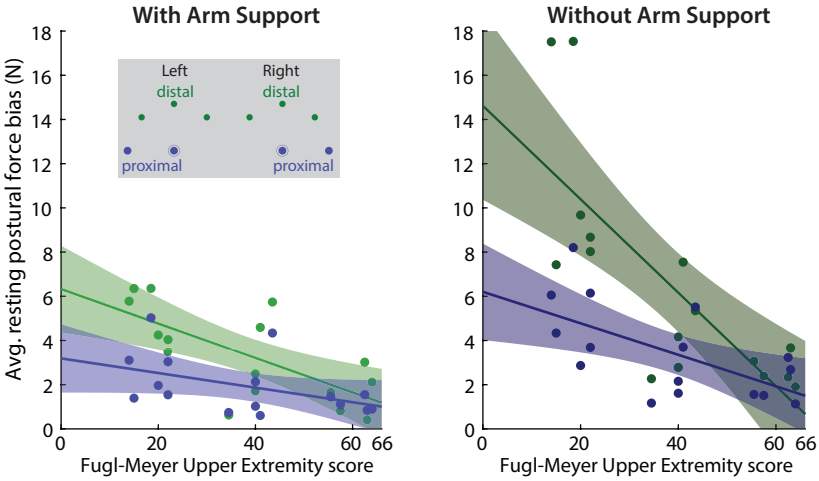

Figure 8: Relationship between resting force biases and abnormal synergies. *Across-patient relationships of FM-UE (/66, higher scores indicating lower impairment) and resting postural force magnitudes, for distal (green) and proximal (blue) target positions, with (left) and without support (right). Note the strong effects of arm support, proximity, and FM-UE. Lines indicate linear fits; shading indicates 95% confidence interval for each fit.*

during movement (Sukal et al., 2007). Yet, Experiment 2 found no relationship between resting postural force biases and active movement control. To further investigate this apparent paradox, we examined the relationship between resting postural force biases and abnormal synergies in further detail. To assess the level of synergy abnormalities for each patient, we measured their Fugl-Meyer scores for the upper extremity (FM-UE), a scale which was designed to capture abnormal muscle synergy after stroke (Brunnstrom, 1966; Fugl-Meyer et al., 1975) and closely corresponds to EMG-based synergy measures (Bourbonnais et al., 1989).

We entered patients' resting postural bias magnitudes into a mixed-effects ANOVA with FM-UE (continuous), Proximity (distal: the three locations furthest from the body, proximal: the two locations closest to the body, Figure 8, top left) and Support (with air sled, without air sled) as factors, evaluating for main effects and interactions. All factors showed significant main effects, with resting postural force magnitudes decreasing with FM-UE (R^2 = 0.27, p 2×10^{-8}), target proximity (η^2 = 0.13, p = 0.00003), and weight support (η^2 = 0.13, p = 0.00004). Significant interactions were observed between FM-UE and both Support (p=0.0062) and Proximity (p=0.0034), with Support and Proximity becoming more important for lower FM-UE scores (i.e. higher overall motor impairment / higher synergy intrusion) as illustrated in Figure 8.

In summary, we made three key observations with regard to abnormal resting postural force biases. First, like abnormal synergies, they were exaggerated when active arm support was required. Second, they were more pronounced in more distal positions where the elbow was more extended; if patients were to actively reach to the same locations, they would have faced increased intrusion of flexor synergy. Third, they scaled with the synergy-based FM-UE. These observations suggest a common mechanism behind resting postural force biases and abnormal synergies.

Discussion

We assessed abnormal resting posture in stroke patients by measuring the resting force biases they involuntarily exerted while their arm was held at different points within a planar workspace (Experiment 1). We found that these resting postural force biases were strongest in more distal positions of the arm, generally pulling the arm toward a flexed position, and were significantly reduced, but nevertheless remained present, when the arm muscles were relieved of the need to support the weight of the arm. We then proceeded to assess reaching and holding control in the same workspace in the presence of arm support (Experiment 2) and examined whether resting postural forces could partially account for deficits in the motor control of reaching and holding still in the same patients. Remarkably, these resting postural force biases did not seem to have a detectable effect upon any component of active reaching but only emerged during the control of holding still after the movement ended. These results suggest a clear dissociation between the control of movement and posture. At the same time, assessing patients' impairment using the FM-UE, a metric designed to measure for abnormal synergies during 3D arm movements, revealed a strong association between resting force biases and abnormal movement synergies; which raises the possibility that the observed dissociation of movement and posture control for planar weight-supported movements may break down for unsupported 3D arm movements. This dissociation raises interesting questions about both the neural architecture responsible for it, and how to approach rehabilitation of the post-stroke arm.

Dissociation between reaching and holding still

Previous research provides evidence for separate control of reaching and holding in the healthy arm – for a review, see (Shadmehr, 2017) and (Jayasinghe et al., 2022). For example, following visuomotor rotation training specific to the outward phase using an out-and-back movement, participants did not transfer this rotation to holding still after a point-to-point reach in the same direction: after the movement was over, and visual feedback was removed, participants' held position drifted from the rotated movement endpoint towards the baseline hold position (Scheidt and Ghez, 2007). There is also neurophysiological evidence for separate control of moving and holding still. A previous study found populations of neurons in macaque M1 that represent mechanical loads during posture or movement but not both (Kurtzer et al., 2005), whereas in another study cortical neurons and spinal interneurons coded parameters related to either movement or posture maintenance (Shalit et al., 2012).

The dissociation reported here between the control of reaching and holding still in the post-stroke arm is consistent with a recently proposed hybrid model, which posits distinct controllers for reaching and for bringing the arm to a stop (Jayasinghe et al., 2022). Our finding that resting posture control does not interact either with the initial reach or bringing the arm to a stop extends this idea, suggesting *three* distinct controllers: one for the initial reach; another for bringing the arm to a stop; and another for control of holding still at the endpoint after movement is over. It should be noted, however, that having distinct neural circuits for reaching and holding does not rule out interactions between the two. For example, as is the case for the control of saccadic eye movements, the holding circuit may integrate information from the moving circuit; we recently found evidence for this in both healthy participants and patients with hemiparesis (Albert et al., 2020).

Potential origins of abnormal resting flexor biases

Experiment 1 revealed several parallels between resting postural force biases and abnormal synergies: a propensity for flexion, mitigation by arm weight support and, a significant correlation between patients' resting postural force biases and their FM-UE scores – a measure designed to assess post-stroke abnormal synergies, which manifest during active movement. These similarities raise the possibility that post-stroke resting postural biases and movement synergies share a generative mechanism. Consistent with this possibility, a study found that externally-imposed elbow flexion led to (involuntary) shoulder flexion and external adduction in stroke patients but not healthy controls, suggesting abnormal synergy patterns do not require active voluntary movement to be expressed (Sangani et al., 2007) – also see (Schmit and Rymer, 2001).

It has been proposed that abnormal resting posture after brain injury can be ascribed to an extrapyramidal system (i.e., other than the corticospinal tract, CST) (Denny-Brown, 1964). Consistent with this suggestion, multiple lines of evidence from animal models point towards reticulospinal tract (RST) involvement in postural control (Deliagina et al., 2007; Lacquaniti et al., 1997; Takakusaki, 2017). Lesions of the monkey ponto-medullary reticular formation resulted in abnormal postures; notably, these were characterized by trunk and limb flexion, elevated shoulders, and arms held close to the body (Lawrence and Kuypers, 1968) mirroring the flexor posture pattern seen after stroke. Several studies in cats also suggest a postural role for the reticulospinal tract. Reticular formation neurons respond to vestibular inputs such as head tilts or whole-body tilts, in line with a role in adjusting posture against gravity (Bolton et al., 1992; Matsuyama and Drew, 2000; Pompeiano et al., 1984). Electrical and chemical stimulation of the reticular formation leads to modulations in muscle tone (Takakusaki et al.,

2016), and reticulospinal neurons display tonic activity patterns related to postural adjustments that precede movement, rather than to the movement itself (Schepens and Drew, 2004).

There is also recent evidence that the RST is the descending system responsible for the generation of large forces during voluntary movement (Glover and Baker, 2022; Tapia et al., 2022). Thus, the accumulated evidence suggests that the RST could control posture and large force production in the upper limb. Upregulation of the RST has also been implicated in the generation of abnormal movement synergies after stroke (McPherson et al., 2018). For example, the ipsilateral RST can facilitate flexors but suppress extensors, a pattern mirroring the flexor synergy (Davidson et al., 2007; Davidson and Buford, 2004).

There appears to be a contradiction, however, between the idea that abnormal postures share a common mechanism with abnormal movement synergies, and our finding that there was no evidence for intrusion of resting biases into any phase of active reaching. A potential explanation for this apparent contradiction is that our experiments were conducted on a 2D surface with weight support. In contrast, the FM-UE scale, a synergy-based measure, is performed by patients in 3D without weight support. It has been shown that for 3D reaching, patients with chronic stroke express intrusive flexor synergies (Zackowski et al., 2004). Weight support – as was used in Experiment 2 – also reduces intrusion of flexor synergies for planar movements (Sukal et al., 2007) and improves planar kinematics (Beer et al., 2007, 2004). Earlier work in a weight-supported planar task found similar degrees of reaching abnormality whether movements were made in or out of synergy (Levin, 1996); more recently, we showed that reaching dexterity can be dissociated from synergy intrusion when arm support is provided (Hadjiosif et al., 2022). Thus, while resting flexor biases and movement-related flexor synergies are both reduced by full weight support, synergies seem to be more so. This is not inconsistent with positing a shared substrate for the abnormalities at rest and during movement, but this substrate might play more of a role in holding still than in moving, and so the consequences of when it is damaged may be more apparent in a task that stresses holding still over movement. We suggest a putative framework below.

We posit that the motor system has separable functional modes for moving vs. holding still and that this is accomplished by differentially weighting the contributions of descending systems that are operative in both modes (Figure 9). The CST is weighted more towards fast and fractionated control during movement, the RST, in contrast, is weighted more towards slower postural control and generation of large isometric forces. In healthy individuals, these two modes are kept in balance by the CST, which has a moderating influence on the RST (Schepens and Drew, 2006) (Figure 9, left). In this framework, the CST is the controller during movement and the modulator during holding still.

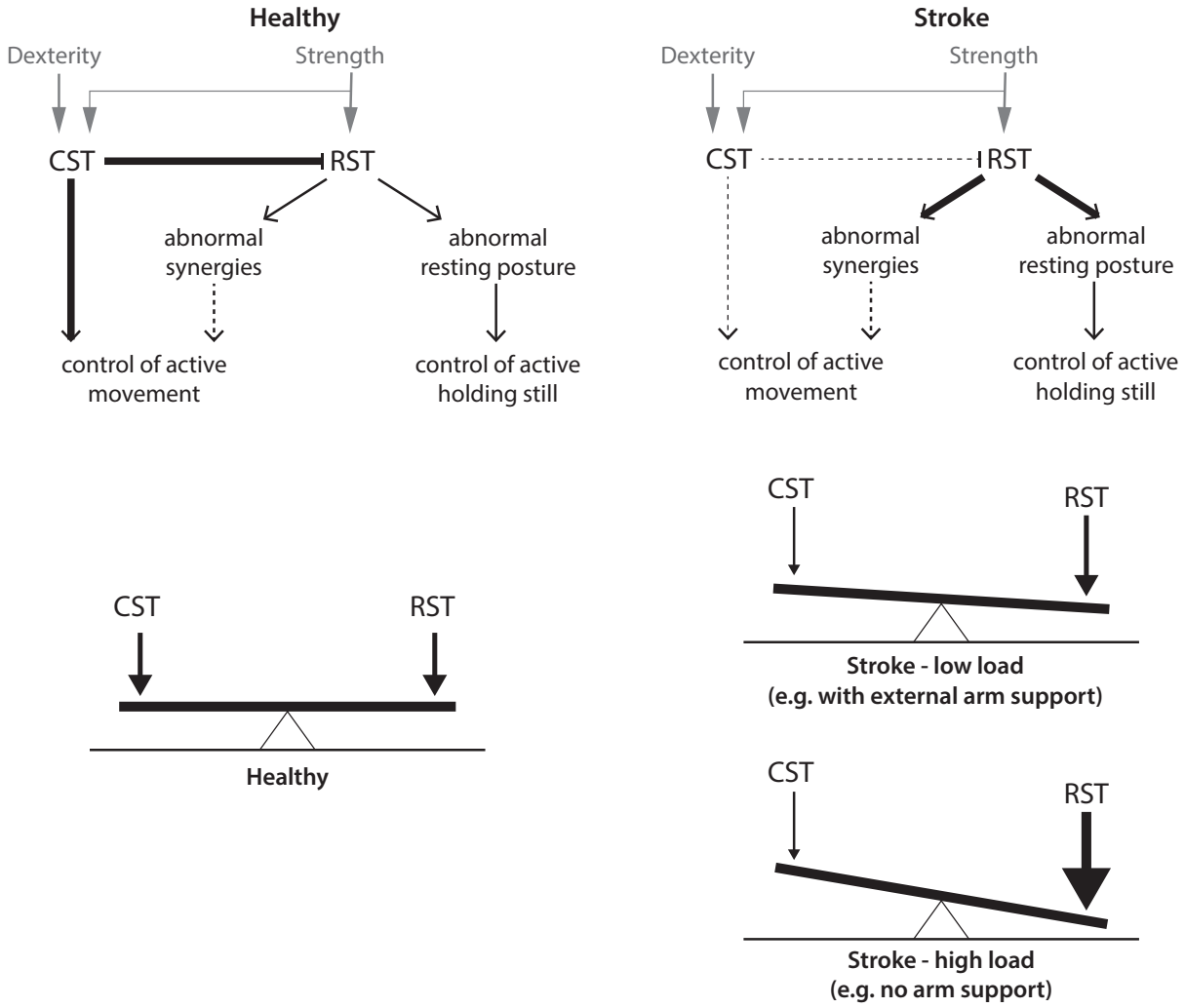

Figure 9: An architecture for the separable control of reaching and holding and spillover effects in stroke.

Damage to the CST after stroke reduces its moderating influence upon the RST (Figure 9, right); influence that is likely further compromised by upregulation of the RST through plasticity mechanisms (García-Alías et al., 2015; Zaaimi et al., 2012). This model can explain our results as follows: As the CST is the dominant system during movement it can still modulate the RST in this mode, especially with weight support, as this reduces RST drive, with the consequence that resting biases do not markedly contaminate active movement. Conversely, the RST is the dominant system for postural control, and can overcome weakened CST modulation, which leads to the resting biases we observed. Thus, weight support allows a weakened CST to keep moving protected from abnormal holding, but it cannot prevent abnormal holding itself. The interesting implication of this model is that synergies are in fact postural abnormalities that spill over into active movement when the CST can no longer modulate the increased RST activation that occurs when weight support is removed (McPherson et al., 2018).

A side question is how the control of decelerating to a stop – which we show here is distinct from the control of holding still after the movement is over – fits within such a scheme. A recent saccade study found that deceleration may be controlled through the cerebellum (Sedaghat-Nejad et al., 2022). In reaching tasks in the mouse, activity in the interpositus nucleus scaled with limb deceleration (Becker and Person, 2019) whereas disruption of the pontine nuclei did not impair movement initiation as much as kinematic variables related to bringing the movement to a stop (Guo et al., 2021).

Increased recruitment of the RST has also been implicated in power grip (Baker and Perez, 2017; Tazoe and Perez, 2017). This may be relevant to our study, as our task had participants actively grasp the handle of the robot for both Experiments 1 and 2. If increased RST recruitment indeed explains abnormal resting postural biases as we discussed in the previous section, a stronger grasp would in turn increase the strength of these biases even further. Moreover, the intermixing of free-reaching and perturbation trials in Experiment 2 could have led to increased uncertainty in environmental dynamics; uncertainty can lead to adjustments such as even stronger grip (Hadjiosif and Smith, 2015). Yet, despite this potential additional RST recruitment, we found that resting biases did not affect active reaching and only switched on after the reach was over; detected when we a applied a perturbing hand force. This result lends further support for separate controllers for reaching vs. holding still.

Another potential source for the resting postural force biases we observe could be abnormally low thresholds (Levin and Feldman, 1994; Powers et al., 1989) or abnormally high gains (Thilmann et al., 1991) of the stretch reflex. Passively extending the elbow, even at low speeds – something Experiment 1 did – can lead to increased muscle activity which may persist after the end of movement (Kanade-Mehta et al., 2022; Levin et al., 2000). This velocity-dependent increase in muscle tone – spasticity – could potentially explain some of the resting force biases measured in Experiment 1. However, in an earlier task where the elbow was passively extended at different velocities, the resulting tonic biceps EMG terminated around the time that the applied elbow extension was completed (Thilmann et al., 1991). And, in recent work, (Kanade-Mehta et al., 2022) used a paradigm similar to Experiment 1 and found that, while resting force biases may initially reflect the velocity at which the arm (passively) approached each test position, this velocity dependence dissipated 2s after the end of passive movement. In our study, resting biases were measured beginning 2s *after* the end of movement, which makes a central rather than a reflex mechanism a more likely culprit.

Conclusions

Our examination of the interplay between abnormalities in moving and holding still in patients making planar reaching movements suggests the existence of two functional modes of control, likely constructed out of differing configurations of the CST and the RST. The components of the paretic syndrome – loss of dexterity, weakness, abnormal resting posture, and intrusive synergies provide insight into how a normal movement is assembled by descending systems. To the degree that hemiparesis is a consequence of the CST losing, to varying degrees, both its direct control over motor neurons and its modulatory influence on the RST, then physiological and behavioral interventions that augment the residual CST may have a plurality of benefits. In support of this, in a recent study of epidural stimulation of the cervical spinal cord in two chronic stroke patients (the rationale behind the stimulation being to amplify residual CST commands) multiple hemiparetic components –strength, dexterity, synergy abnormalities – improved simultaneously (Powell et al., 2023).

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Competing interests

The authors report no competing interests.

ID	Age (5y range)	Sex	Time since stroke	Handed-ness	Paretic arm	FM-UE (/66)	ARAT (/57)
S001	76-80	M	2y	Right	Left	57.5	57
S002	51-55	M	6y	Right	Left	40	47.5
S003	66-70	F	7y	Right	Right	34.5	19
S004	26-30	F	5y	Right	Left	55.5	43.5
S005	76-80	M	13mo	Right	Right	43.5	34
S007	51-55	F	2mo	Left	Right	63	57
S008	51-55	F	14mo	Right	Left	41	25
S009	56-60	F	5y	Right	Left	22	3
S010	66-70	M	5y	Right	Left	20	12
S011	41-45	F	20mo	Right	Right	64	57
S012	46-50	M	6y	Right	Left	18.5	6.5
S013	66-70	M	9y	Right	Left	14	8
S014	41-45	F	16mo	Right	Left	40	39.5
S015	61-65	F	10y	Right	Left	22	4.5
S016	36-40	F	21mo	Amb.	Right	62.5	57
S017	46-50	M	3mo	Right	Left	15	3

Table 1: Patient characteristics. *FM-UE: Fugl-Meyer Assessment for the Upper Extremity; ARAT: Action Research Arm Test.*

	Stroke patients	**Controls**
N	16	9
Age	58.5±17.8	62.6±15.2
Gender	7M/9F	3M/6F
Paretic side	11L/5R	n/a
FM-UE	38.3±18.2	66.0±0.0
ARAT	29.6±21.8	57.0±0.0
MoCA	24.9±3.1	28.1±1.6
Time since stroke	[2mo,10y]	n/a

Table 2: Summary of patient and control characteristics. *FM-UE: Fugl-Meyer Assessment for the Upper Extremity (/66); ARAT: Action Research Arm Test (/57). MoCA: Montreal Cognitive Assessment (/30).). Here, ± indicates standard deviation.*

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