Active force perception depends on cerebellar function

Bhanpuri NH, Okamura AM, Bastian AJ. Active force perception depends on cerebellar function. J Neurophysiol 107: 1612–1620, 2012. First published December 21, 2011; doi:10.1152/jn.00983.2011.—Damage to the cerebellum causes characteristic movement abnormalities but is thought to have minimal impact on somatosensory perception. Traditional clinical assessments of patients with cerebellar lesions reveal no perceptual deficits despite the fact that the cerebellum receives substantial somatosensory information. Given that abnormalities have been reported in predicting the visual consequences of movement, we suspect that the cerebellum broadly participates in perception when motor output is required (i.e., active perception). Thus we hypothesize that cerebellar integrity is essential for somatosensory perception that requires motor activity, but not passive somatosensory perception. We compared the perceptual acuity of human cerebellar patients to that of healthy control subjects in several different somatosensory perception tasks with minimal visual information. We found that patients were worse at active force and stiffness discrimination but similar to control subjects with regard to passive cutaneous force detection, passive proprioceptive detection, and passive proprioceptive discrimination. Furthermore, the severity of movement symptoms as assessed by a clinical exam was positively correlated with impairment of active force perception. Notably, within the context of these perceptual tasks, control subjects and cerebellar patients displayed similar movement characteristics, and hence differing movement strategies are unlikely to underlie the differences in perception. Our results are consistent with the hypothesis that the cerebellum is vital to sensory prediction of self-generated movement and suggest a general role for the cerebellum in multiple forms of active perception.

sensory discrimination threshold; proprioception; forward model; ataxia

MANY SENSORY PERCEPTS involve action and movement—for example, when opening a door we can tell if it is stiff or compliant, heavy or light. This kind of active force perception appears to depend not only on peripheral sensory signals but also on central motor commands (Gandevia and McCloskey 1977; Jones and Hunter 1983). For example, increased grip force on slippery surfaces produces overestimation of weight (Flanagan et al. 1995) and horizontal load (Flanagan and Wing 1997). This suggests that the nervous system has a means of predicting how motor commands will normally move the arm and hand-held objects (Wolpert and Flanagan 2001). The cerebellum is a likely candidate for this type of prediction, since it is thought to contribute to movement coordination using an internal model of body dynamics (Kawato 1999). In addition, the cerebellum receives both effferent copies of motor commands and sensory information from the periphery (Dow and Moruzzi 1958; Holmes 1917; Kawato 1999) and has distinct projections to brain areas important for perception (Dum and Strick 2003).

Historically the cerebellum has been thought to have a limited role in basic perceptual abilities such as hearing, vision, smell, and somatosensation (Dow and Moruzzi 1958; Holmes 1917; Maschke et al. 2003), yet neuroimaging studies have shown that the human cerebellum is active during somatosensory processing (Gao et al. 1996) as well as visual and auditory perceptual tasks (Baumann and Mattingley 2010). It has also been reported that cerebellar patients have some deficits in visual motion perception during a tracking task (Ivry and Diener 1991) and do not properly update the visual consequences of self-generated movements (Synofzik et al. 2008). Thus the cerebellum may only be important for percepts that involve movement production. One possible mechanism for certain perceptual deficits is that the cerebellum is essential to making sensory predictions of outgoing motor commands (Blakemore et al. 1998; Miall et al. 2007; Paulin 1993; Synofzik et al. 2008; Xu-Wilson et al. 2009). If cerebellum-dependent sensory predictions are ultimately combined with sensory information from the periphery in order to form percepts, then we predict that cerebellar patients should be impaired at an array of active perceptual tasks (including active force perception) but not passive perceptual tasks. On the other hand, it is possible that perceptual tasks do not rely on sensory predictions of motor commands, in which case we would predict that patients would exhibit normal active perception.

Here, we designed experiments to assess active and passive perceptual thresholds in the somatosensory domain with limited visual information. We recruited patients with cerebellar lesions and age-matched control subjects to participate in the various perceptual tasks. Specifically, we tested for patient impairment with regard to active force perception and also verified that patients had normal passive cutaneous mechnanoreception (Holmes 1917) and normal passive position proprioception (Holmes 1917; Maschke et al. 2003).

MATERIALS AND METHODS

Subjects

We studied 11 patients with cerebellar deficits but no clinical signs of sensory loss and 11 age-, sex-, and handedness-matched control subjects without any known neurological impairments (Table 1). All subjects gave informed consent to the protocols approved by the Johns Hopkins Institutional Review Board. Six patients were diagnosed with...
a genetically defined spinocerebellar ataxia type 6 (n = 5) or type 8 (n = 1). Four patients presented with symptoms of autosomal dominant cerebellar ataxia type III, an inherited disorder with pure cerebellar signs but no definite genetic testing. One patient presented with symptoms of sporadic adult-onset cerebellar ataxia, a disorder with pure cerebellar signs but no familial history. There was no evidence of atrophy to the brain stem or spontaneous nystagmus for these patients. We quantified the severity of cerebellar impairments with the International Cooperative Ataxia Rating Scale (ICARS; Trouillas et al. 1997), which assigns higher scores to patients with greater impairments in walking, balance, limb control (kinetic), speech, and eye movements. For the patient group, the mean total ICARS was 45.5 (SD 21.8, range 14–79; maximum possible score 100). The mean kinetic portion of the ICARS was 19.6 (SD 10.8, range 1–40; maximum possible score 60).

Table 1. Characteristics of subjects

<table>
<thead>
<tr>
<th>Subject</th>
<th>Age, yr</th>
<th>Sex</th>
<th>DH</th>
<th>Diagnosis</th>
<th>Total (/100)</th>
<th>Kinetic (/52)</th>
<th>Cutaneous threshold (R-L, g)</th>
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<td>M</td>
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<td>R</td>
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<td>4</td>
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<td>R</td>
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<td>L</td>
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<td>45</td>
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<td>CRB group</td>
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<td>M</td>
<td>6/11</td>
<td>L</td>
<td>1/11</td>
<td>CRB group</td>
<td>56.7 ± 10.5</td>
</tr>
</tbody>
</table>

Group data are means ± SD. ICARS, International Cooperative Ataxia Rating Scale; CRB, cerebellar subject; CNT, control subject; g, grams; M, male; F, female; DH, dominant hand; L, left; R, right; ADCA III, autosomal dominant cerebellar ataxia III; SCA, spinocerebellar ataxia; Sporadic, sporadic adult-onset cerebellar ataxia. *Performed task 4 (position difference threshold); †did not perform task 3 (movement detection threshold).

Tasks 1 and 2: Torque and Stiffness Discrimination Tasks

Throughout these tasks, two yellow boundary lines were displayed at elbow angles of 75° and 105°. Subjects were told to stay within the boundary lines, which turned red if their arm moved outside the designated range. This was the only visual information they were given, as subjects could not see their arm directly nor was it displayed to them. If subjects moved outside the boundary in more than half the trials within a set, the set was repeated. (This occurred for <15% of subjects.) Thus subjects had to rely on proprioceptive cues to determine arm location. Each trial consisted of a comparison between two subtrials. As described in Fig. 1A, at the beginning of each subtrial, a blue ring appeared just inside the 75° boundary, at 76°, and the background was colored red. After the subject moved the elbow to 76°, the ring filled with color, indicating to the subject that he/she was in the start position. Next, the background changed to green and the robot began to produce torque.

For the torque task, the robot produced a constant extension torque of 0.40, 0.60, 0.80, 0.90, 1.00, 1.10, 1.15, 1.20, 1.25, 1.30, 1.40, 1.50, 1.60, 1.80, or 2.00 Nm. The torque was ramped up over 1 s, remained constant for 5 s, and then ramped down over 1 s (Fig. 2, B and C, 1st column). The ramp duration was chosen to be as quick as possible without introducing unwanted vibrations due to torque discontinuities. Subjects were instructed to ignore the ramping up of the torque and to focus on the constant “force” during the subtrial, which would cause extension if they remained passive. As mentioned above, subjects were required to maintain an elbow angle within 75° and 105° and, hence, applied flexion torque to counter the robot. At the end of the subtrial, the background color changed to red. The process was repeated for the second subtrial, with the only difference being the torque magnitude. The torque magnitude during one of the subtrials was always the “standard,” 1.20 Nm. (The other subtrial magnitude was the “comparison.”) Each trial was randomized as to whether the standard subtrial was presented first or second. According to the “Method of Limits for Difference Thresholds” as described by Geisler (1997), at the end of each trial subjects declared verbally whether the constant torque felt “stronger” on subtrial “one” or “two”...
The practice set ended when subjects gave five consecutive correct trials. The practice set was composed of a random trial sequence with comparison magnitudes of either 0.40 or 2.00 Nm. Understood the protocol.

The task began with a practice set to ensure that participants understood the protocol. The practice set was composed of a random trial sequence with comparison magnitudes of either 0.40 or 2.00 Nm. The practice set ended when subjects gave five consecutive correct responses. Next, subjects performed the experimental sets. The order of comparison magnitudes for a given experimental set was determined with the method of limits (Gescheider 1997). Descending sets began with comparison magnitudes well above the standard, and then on each subsequent trial the magnitude was decreased until the comparison was well below the standard. (The order of ascending sets was the opposite.) For each set, an upper transition point was computed by taking the lowest comparison magnitude for which the subject gave an incorrect or “equal” response and averaging it with the next highest magnitude tested. A lower transition point was computed by taking the lowest comparison magnitude for which the subject gave an incorrect or “equal” response and averaging it with the next lowest magnitude tested. Each subject completed four sets, alternating between descending and ascending sets. The upper threshold was estimated by the average of the four upper transition points, and the lower threshold was estimated by the average of the four lower transition points, for the given subject. Each set consisted of an average of ~11 trials, ranging between 9 and 13 trials. Depending on set length and subject response time, each set took ~5–6 min. Subjects were given breaks of 1–2 min between sets and were permitted to take longer breaks if requested.

The stiffness task was similar to the torque task with the exception that the robot torque was not constant during the subtrials but rather was linearly related to the angular distance from the start position (Fig. 2, B and C, 2nd column). Each subtrial simulated moving against a spring with a specific stiffness such that the torque was zero at the start position and extension (outward) torque was applied as the arm was rotated in flexion (inward). The stiffness magnitude on a given trial was 1.50, 2.50, 3.00, 3.50, 4.00, 4.25, 4.50, 4.75, 5.00, 5.50, 6.00, 6.50, or 7.50 Nm/rad. The standard stiffness was 4.50 Nm/rad. Subjects were instructed that the robot would provide a force similar to “pushing against a spring” or “stretching a rubber band,” meaning that more flexion would result in more “force.” They were encouraged to explore the workspace, but, as in task 1, they were required to maintain an elbow angle within 75° and 105°. Once again, the only visual information regarding arm location was the boundary lines that changed color if the arm moved outside of the designated range.

A practice set in which the trials had comparison magnitudes equal to 1.50 or 7.50 Nm/rad preceded the experiment. As in task 1, during
the experimental sets the comparison stiffness was determined with the Method of Limits for Difference Thresholds (Gescheider 1997). Each trial was randomized as to whether the standard subtrial was presented first or second. At the end of each trial, subjects declared verbally whether the external environment felt “stiffer/more resistive” on subtrial “one” or “two” or if they felt “equal.” It is important to note that subjects were not asked to report their intrinsic joint stiffness, but rather they were asked to discriminate between externally imposed forces that were characterized by stiffness. Thus success in the task depended on combining information about movement amplitude and external torque (Jones and Hunter 1990) but was unrelated to controlling and maintaining intrinsic joint stiffness. Set length, set duration, break frequency, and break duration were similar to the torque task.

Task 3: Passive Proprioceptive Detection Task

Subjects were instructed to remain passive and allow the robot to move their arm while vision of the arm was blocked. Before each trial, the forearm was “reset” to a start position of 90° elbow flexion (Fig. 1B). A blue circle appeared briefly, indicating the start of the trial, and then the elbow was rotated in flexion to a magnitude of 0°, 0.2°, 0.4°, 0.6°, 0.8°, 1.0°, 1.2°, 1.6°, 2.0°, 2.4°, or 3.0°. A proportional-integral-derivative (PID) feedback controller was implemented in order to move the forearm at a steady velocity with mean 0.3°/s and standard deviation 0.01°/s across trials (Fig. 2, B and C, 3rd column). Appropriately tuned PID controllers produce smooth, consistent movements and can correct for external disturbances (Spong et al. 2006). Before each movement there was a random delay of 1–2 s, and after the end of the movement there was a random delay of 4–5 s before a red circle appeared, indicating the end of the trial. Subjects were told that movement could occur at any time before the red circle appeared. Because of the delays of random duration, the latency of the red circle appearance was an unreliable cue for movement length. Thus, although the total trial time varied, duration alone could not provide enough information regarding movement occurrence. (Importantly, in pilot studies we compared the method described here to a similar task in which each trial took the same amount of time, i.e., the longest trial duration. We found that both methods resulted in similar thresholds, while the latter method took significantly more total time and resulted in greater subject fatigue.)

According to the “Method of Limits for Absolute Thresholds” (Gescheider 1997), subjects then expressed verbally “yes” or “no” as to whether or not they felt a movement during the trial. Prior to the experimental sets, subjects conducted a practice set that consisted of a random sequence of trials with the extreme magnitudes 0.0° and 3.0°. During experimental sets, the order of magnitudes presented to the subjects followed the method of limits (Gescheider 1997). The procedure begins by first presenting a stimulus well above (descending set) or below (ascending set) threshold, and then, with each following trial, the stimulus strength is changed by a small amount in the direction of the threshold. The set ends when the subject’s response changes. The two magnitudes between which a response change occurs are averaged to compute the transition point. Each subject completed four sets, alternating between descending and ascending sets. The average of the four transition points provided the estimate of the absolute threshold for the given subject. Each set consisted of an average of about six trials, ranging between three and nine trials. Depending on set length and subject response time, each set took ~5–7 min. Subjects were given breaks of 1–2 min between sets and were permitted to take longer breaks if requested. Because of the limited availability of 1 patient, only 10 patients and 10 matched control subjects completed this task.

Task 4: Passive Proprioceptive Discrimination Task

Six patients and six matched control subjects performed task 4 on a return visit to the laboratory. Each trial consisted of two subtrials during which the subject’s forearm was rotated different magnitudes while the subject remained passive and vision of the arm was blocked (Fig. 1C). First, the subject was moved to the start position (75°) and a blue circle appeared briefly to indicate the beginning of the subtrial. Next, with the PID controller, the commanded velocity was ramped up over 250 ms (to minimize possible torque transients) and held constant at 5°/s (SD 0.05°/s), until the desired displacement was achieved (Fig. 2, B and C, 4th column). After a random delay between 7.5 and 8 s from the start of the subtrial, a red circle appeared to indicate the end of the subtrial. (In contrast to task 3, the latency of red circle appearance was consistently longer than the duration of the longest possible movement. In this case we used a more conservative approach to the timing of task events because subjects did not express excessive fatigue during pilot experiments—presumably because of higher-velocity, shorter-duration movements.)

The magnitude of the comparison distance was determined with the Method of Limits for Difference Thresholds (similar to tasks 1 and 2). At the end of each trial, subjects declared verbally whether the movement was “farther/longer distance” on subtrial “one” or “two” or if they felt “equal.” The task began with a randomized practice set in which the comparison magnitudes were either 2.0° or 18.0°, and five consecutive correct responses were required before the experimental sets began. Each set consisted of an average of ~11 trials, ranging between 9–13 trials. Depending on set length and subject response time, each set took ~5–6 min. Subjects were given breaks of 1–2 min between sets and were permitted to take longer breaks if requested. It should be noted that any magnitude (i.e., distance) comparison must inevitably involve velocity and duration comparisons as well. In the task described here, velocity was constant and duration varied for different magnitude trials. Alternatively, duration could have been constant and velocity could have varied for different magnitude trials, or a third possibility is that velocity (and the corresponding duration) could have been randomized from trial to trial to reach different magnitudes. In all cases, if subjects are not explicitly told which parameters are being varied or held constant, subjects could use information regarding all three parameters to assess movement magnitude. Thus passive proprioception, as described here, specifically involves position sense, duration sense, and velocity sense. We opted to keep velocity constant because the robot controller was less optimal at high velocities.

Electromyographic Recordings

Electromyographic (EMG) recordings were collected with the Bagnoli EMG system (DelSys, Boston, MA). Surface electrodes were placed on three muscles in the tested arm: brachioradialis, biceps brachii, and triceps brachii. The amplifier gain was 10,000 for all channels, and the sampling rate was 1 kHz. For tasks in which subjects were instructed to remain passive, EMG signals were monitored and trials with muscle activity during these tasks were discarded (typically ≤5% of trials for a given subject).

Analysis

Discrimination tasks. The average upper and lower thresholds (UT, LT) were calculated for each subject. The point of subjective equality (PSE) was estimated as the average of the UT and LT for each subject. The Weber fraction (WF) was computed as

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WF = (UT - LT)/(2 × PSE).

The individual subject WFs were then used to compute the average WF for each of the groups (patients and control subjects).

Detection task. For each subject, the average absolute threshold was calculated across the four sets. The individual subject means were then used to compute the averages for each of the groups. Group differences in various parameters (WF, PSE, position threshold, movement metrics) for each task were computed with a t-test for independent samples with separate variance estimates after testing for normality of data distribution with the Lilliefors test (Statistica, Tulsa, OK). Within-group comparisons of parameters (WF, PSE, and position threshold) were computed with a t-test for dependent samples. In addition, correlation analyses were performed on the parameters (WF, PSE, and position threshold, movement metrics) with respect to other parameters and with respect to ICARS subscores for patients by computing Pearson's product-moment correlation coefficient and corresponding significance levels.

RESULTS

In task 1, subjects pushed against a constant torque produced by the robot about the elbow, while keeping the forearm within the designated 30° range. Using the paradigm illustrated in Fig. 1A, we measured the difference threshold, which is the magnitude of stimulus that could just be distinguished from a fixed standard stimulus of 1.2 Nm. The difference thresholds were then used to compute WFs, a metric for comparing perceptual sensitivity across different magnitudes and modalities (Gescheider 1997). Low WFs indicate greater sensitivity, i.e., smaller differences between the standard and test magnitudes are required for discrimination), whereas high WFs indicate less sensitivity. In contrast to their success in perceiving passive forces (discussed below), patients were impaired at discriminating between constant torques when muscle activity was required to resist external torques (P = 0.021; Fig. 3A). Thus cerebellar degeneration appears to worsen active force discrimination. Furthermore, within the patient group, torque WFs were significantly correlated with the ICARS kinetic functions score (Pearson’s correlation r = 0.72, P = 0.013; Fig. 3B). Patients with more severe cerebellar signs were more impaired at torque discrimination.

We used two metrics, maximum elbow angle and standard deviation of elbow angle, to test for discrepancies in the amount of movement between groups. Control subjects and cerebellar patients exhibited a variety of different position profiles as demonstrated by exemplary trials for task 1 (Fig. 4A). The metrics for these example trials are shown in Fig. 4, B and C, to show how they correspond to different position profiles. Importantly, the movement metrics of all subjects, averaged across all trials, in task 1 (and task 2, described below) showed no systematic differences across groups (all P > 0.19; Fig. 4, D and E). Consequently, differences in perceptual thresholds between control subjects and cerebellar patients cannot be attributed to differing movement strategies. Additionally, among the patient group neither maximum elbow angle nor standard deviation of elbow angle was significantly correlated to ICARS scores for tasks 1 and 2 (all P > 0.21). Therefore, although certain patients demonstrated more variability and intention tremor during rapid, targeted movements (one of the key assessments for the ICARS rating) relative to their peers, those patients did not systematically move more erratically within the context of these tasks.

In task 2, we assessed stiffness discrimination, a second, more complex form of active force perception. Stiffness perception requires a direct comparison between sensed force and position information (Jones and Hunter 1990). The task 2 trial sequence was the same as task 1 (Fig. 1A), but the applied torques were not constant. Instead they scaled with elbow angle, thereby simulating a virtual spring with a different stiffness (Nm/rad) on each trial. Subjects were encouraged to move away from the start position in order to feel the stiffness on each trial, but were restricted to the same 30° range as in task 1. For a given group, stiffness WFs significantly greater than torque WFs would indicate that those subjects were impaired at estimating the ratio between sensed torque and displacement. While the patients’ stiffness WFs were higher than those of control subjects (P = 0.026; Fig. 3C), both patients and control subjects were not different from their respective torque WFs (patients P = 0.12, control subjects P = 0.82; compare Fig. 3, A and C). Moreover, across all subjects, stiffness perception was significantly correlated with torque
perception (Pearson’s correlation \( r = 0.80, P < 0.001 \)). Although stiffness WFs were positively correlated with ICARS kinetic functions score among the patient group, the correlation was not significant (Pearson’s correlation \( r = 0.49, P = 0.12 \)). In sum, the task 2 results confirm that the cerebellum contributes to active force perception but indicate that it is not important for gauging the relationship between sensed torque and movement amplitude. This form of multimodal perception may be a function of posterior parietal cortex (Stein and Stanford 2008).

To ensure that movement detection was intact in patients, we performed task 3 to measure the absolute threshold for position proprioception (i.e., the smallest detectable change in elbow angle; Fig. 1B). There was no difference between groups (\( P = 0.89; \) Fig. 3D). In fact, the observed values (mean \( \pm SE \): patients \( 0.91 \pm 0.17^\circ \), control subjects \( 0.88 \pm 0.13^\circ \)) were similar to those reported previously despite differences in the robot apparatus and psychophysical methods (1.15\(^\circ\), 1.03\(^\circ\)) (Maschke et al. 2003). Thus this facet of passive proprioception does not appear to be cerebellum dependent, although it has been reported that, with regard to proprioception, both duration sense and velocity sense may involve the cerebellum (Grill et al. 1994).

The initial finding that patients performed worse than control subjects at tasks 1 and 2, but not task 3, we designed task 4 to examine patients’ ability to recall and compare sensations in a passive task. In task 4, proprioceptive difference thresholds were measured by instructing subjects to compare passive displacements of different amplitudes (Fig. 1C). Again, the method of limits protocol for discrimination thresholds was employed to compute the WF. We were able to retest a subgroup of six patients with impaired torque perception (torque WF > mean control torque WF) and matched control subjects. The results clearly indicate that patient impairments in torque and stiffness thresholds (tasks 1 and 2) were not due to memory problems, because the patient subgroup were significantly worse at tasks 1 and 2 (task 1 \( P = 0.0011 \), task 2 \( P = 0.0061 \); Fig. 5, A and B) but similar to their control counterparts at task 4 (\( P = 0.83 \); Fig. 5C), which included a comparable memory demand. Furthermore, potential disruption of duration and velocity sense due to cerebellar damage (Grill et al. 1994) did not seem to impair patient performance in this task, even though duration and velocity information could, theoretically, be combined with position sense in order to complete the task (see Task 4: Passive Proprioceptive Discrimination Task). Finally, similar to the larger groups, the subgroups were not significantly different with regard to task 3, movement detection (\( P = 0.47; \) Fig. 5D).

As mentioned above, the patients showed no deficits in passive cutaneous mechanoreception based on a monofilament detection assessment at the index finger of the dominant hand. The threshold for all subjects was \( \leq 0.4 \, g \), which is normal for the given subject age (Semmes et al. 1960). Thus the component of force perception mediated by cutaneous mechanoreceptors was not disrupted in patients. It is therefore unlikely that the cause of impaired torque discrimination in patients is due to poor mechanoreception.

**DISCUSSION**

The key finding in this study is that cerebellar patients were impaired in the perception of external torque and stiffness but unimpaired in passive position proprioception at the same joint and passive mechanoreception at the same hand. Thus the deficit is specific to active force perception. The severity of ataxia (kinetic score) was significantly correlated with reduced torque perception. Additionally, our results suggest that within the constraints of the experiments described, stiffness discrimination is closely related to torque discrimination for both control subjects and patients. Thus perceiving torque during self-generated movement appears to be cerebellum dependent, while perceiving the ratio between torque and displacement seems to depend on other brain areas. The results predict that patients would also have difficulty with other types of load discrimination that require movement such as object heaviness during wielding (Angel 1980; Dow and Moruzzi 1958) but not...
passive heaviness perception (e.g., when an object is placed on the hand supported by a solid surface).

As mentioned above, the proprioception discrimination task (task 4) may have involved a mix of information including position and velocity proprioception and duration sense, even though subjects were instructed to focus on movement distance. Presumably, the same information contributes to position sense during the torque and stiffness tasks (tasks 1 and 2). Our results indicate that deficits in torque and stiffness discrimination are not due to underlying problems with position perception (arising from a combination of position and velocity proprioception and duration sense). Additionally, since it has been suggested that velocity proprioception and duration sense are indeed impaired after cerebellar damage (Grill et al. 1994), it is likely that, within the context of the experiments described here, subjects relied more heavily on position sense rather than velocity or duration sense. Otherwise, we would have expected control subjects to perform better at task 4 relative to the patient group.

The specific thresholds and WFs computed in this study undoubtedly depend on the specific details of the task sequence and overall methodology. The method of limits was chosen as a compromise between overall task duration and sensitivity of perceptual measurements. It is possible that a more rigorous and time-consuming methodology (e.g., “Method of Constant Stimuli,” Gescheider 1997) would have resulted in slightly different WFs than those computed here (perhaps shifted up or down). However, the important conclusions of this study are based on the perceptual differences observed between the patient and control groups, which would presumably have been seen if a different psychophysical method had been employed.

An important consideration is that the amount of movement during force and stiffness discrimination tasks can influence subjects’ ability to resolve external loads (Tan et al. 1995). It is possible that differences in movement or exploration strategy during the constant torque (task 1) and stiffness (task 2) tasks caused the observed group differences in perceptual sensitivity. In tasks 1 and 2, subjects employed varying movement strategies, as they were not given explicit instructions other than to stay within the 30° range. However, we found no differences between patients and the matched control group in maximum elbow angle and standard deviation of elbow angle for either of the two tasks. Therefore, we concluded that the impairments in torque and stiffness discrimination were not due to differing movement patterns between groups.

Perceptual differences observed in this study could potentially be attributed to differences in onset acceleration between tasks. In other words, abrupt changes in acceleration or external torque could activate different sensory signals and perhaps elicit reflexes that could influence perception. However, as explained in the task description and demonstrated in Fig. 2, B and C, bottom, all of the tasks were designed to have gradual changes in externally applied torque, and thus onset acceleration was relatively low across all of the different tasks described. Therefore, we concluded that the observed perceptual thresholds were not impacted by abrupt changes in acceleration.

It is possible that the perceptual deficits we observed in cerebellar patients were due to changes in fusimotor drive (Gilman and McDonald 1967). Within the fusimotor system, gamma motoneurons modulate muscle spindle sensitivity (important for proprioception) by altering the tension in intrafusal muscle fibers. If the cerebellum is specifically important for gamma motoneuron-driven increases in sensitivity during self-generated movement but not during rest, then cerebellar patients would show impaired active but not passive perception as seen here.

However, we favor the possibility that the role of the cerebellum in active force perception is more sophisticated than simply increasing receptor sensitivity during movement based on its putative function in motor control. We propose that the cerebellum may be important for sensory prediction, which is important for accurate movement control (Kawato 1999; Miall et al. 2007; Wolpert and Flanagan 2001; Xu-Wilson et al. 2009), and might be essential for distinguishing internal from external sensation (Blakemore et al. 1998; Gellman et al. 1985). It is possible that the cerebellum modulates the fusimotor system based on predictions of movement outcomes rather than simply causing an increase in receptor sensitivity, or perhaps the cerebellum sends signals of movement prediction directly to the parietal cortex.

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The results presented here build upon findings that the cerebellum is important for updating predictions of movement outcome following a visual rotation (Synofzik et al. 2008). Theoretically, predictions of sensory changes due to self-generated movement would rely on a forward dynamic model that receives copies of motor commands and has knowledge of the limb’s physical properties (Kawato 1999; Wolpert and Flanagan 2001). These sensory predictions could contribute to active force discrimination by providing an error signal between predicted and expected movements, and hence indicate changes in external load. A malfunctioning (i.e., unreliable) forward model would account for movement variability characteristic to cerebellar damage (Dow and Moruzzi 1958; Holmes 1917; Trouillas et al. 1997) and the impaired active force perception observed in this study. Importantly, our results from the passive tasks are in line with the notion of the cerebellum acting as a forward model, because a corrupt forward model would not impair passive somatosensory perception. In addition, the results presented here are in accordance with the finding that the size-weight illusion is preserved in patients with cerebellar degeneration (Rabe et al. 2009), which is thought to rely more on cognitive expectations of constant material density than on accurate forward models (Flanagan and Beltzner 2000). We do not propose that the cerebellum is itself integrating and processing different modes of information that lead to perception, but, rather, it is likely providing one of several signals that may be integrated by the parietal cortex (Stein and Stanford 2008). Similarly, evidence from a recent study suggests that visual motion perception in cerebral cortex relies on relevant signals from the cerebellum (Händel et al. 2009). If the cerebellum is indeed critical to sensory predictions of self-produced movements, or simply increasing receptor sensitivity during all movements, it is likely to play a role in other forms of active sensory perception (e.g., active proprioception, stereognosis).

Finally, the results of this study have clinical relevance. They suggest that, in addition to well-known movement abnormalities, cerebellar patients have clear perceptual deficits during self-generated movement. They have difficulty discriminating between the heaviness of different objects (during movement; Angel 1980). For example, during lifting patients may not be able to readily perceive whether an opaque cup is full or empty, which would serve to exacerbate problems with moving the cup accurately. Another practical example is that patients may have difficulty distinguishing whether an accelerator pedal is stiff or compliant and thus would presumably struggle with driving an unfamiliar car.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: N.H.B., A.M.O., and A.J.B. conception and design of research; N.H.B. performed experiments; N.H.B. analyzed data; N.H.B., A.M.O., and A.J.B. interpreted results of experiments; N.H.B. prepared figures; N.H.B. drafted manuscript; N.H.B., A.M.O., and A.J.B. edited and revised manuscript; N.H.B., A.M.O., and A.J.B. approved final version of manuscript.

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