Interlimb coordination deficits during cyclic movements in cerebellar hemiataxia

Abstract—The authors report a 35-year-old man whose unilateral cerebellar lesion resulted in marked deficits in coordinating simultaneous cyclic movements of the arm and leg on his ipsilesional side. He exhibited no such deficits when making simultaneous movements of the contralesional limbs or when moving paired left and right limbs. Thus, the cerebellum, which is already known to underlie within-limb interjoint coordination, also contributes to coordination between limbs.

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The cerebellum plays a vital role in the coordination of single limb movements. In single joint (e.g., elbow) movement, cerebellar lesions result in problems with the relative timing or amplitude of activity or both in the agonist and antagonist muscles.[1-4] Multijoint (e.g., elbow and shoulder) movement is also impaired, beyond what may be expected from single joint movement impairment.[5,6]

Within-limb incoordination is a well-described characteristic of cerebellar disease. However, the success of many everyday actions depends on coordinating movement across limbs. For example, walking and swimming are cyclic activities in which the different limbs move in a controlled phase relation. In this report, we show impaired coordination of in-phase and antiphase cyclic movements of the arm and leg in an otherwise fit young man who had a discrete lateralized cerebellar insult, leading to classic features of cerebellar hemiataxia.

Case report. Our patient is a left-handed man who was aged 35 years at the time of testing. Three years earlier, he had had a left cerebellar hemisphere hemorrhage from an arteriovenous malformation (figure 1), which subsequently underwent therapeutic embolization. He made a fair recovery. At the time of testing, he was in good general health, neurologically stable, and taking no medication. The family history was unremarkable for neurologic disease.

He exhibited typical features of cerebellar dysfunction. In particular, he had dysdiadochokinesia and past pointing with his left arm. There was marked ataxia of the left leg on the heel-shin test. The right limbs were normal. His gait was broad based and a little ataxic; he was unable to walk heel to toe; and Romberg's test was positive. Tone, power, deep tendon reflexes, and light touch sensation were normal throughout. There were no lower cranial nerve signs.

Methods. The patient and five control subjects (one female) of similar age were tested. All participants provided written informed consent; the local ethics committee approved the study. Reflective markers were placed on the subject's back and on his right and left elbow, wrist, knee, and ankle joints. A six-camera Vicon motion capture system (Oxford, UK) was used to track three-dimensional movement trajectories at 120 Hz. Participants were asked to move ("swing") the following limb pair combinations at their preferred frequency ("most comfortable, least strenuous") either in-phase (the limbs move forward and backward together) or in antiphase (one limb moves forward as the other moves backward): right arm–left arm (RALA), right arm–left leg (RALL), right arm–right leg (RARL), left arm–right leg (LARL), and left arm–left leg (LALL). Arm movements were made about the shoulder, and leg movements were made about the knee. All tasks were performed seated, except for RALA, which was performed standing up. Each trial lasted 20 seconds.

Results. Figure 2 shows representative trials from the patient in four conditions. In condition RARL, there is a stable phase relation with the arm leading (as is the case in control subjects). RALL also shows a relatively stable phase relation with the contralesional "good" arm leading. Interestingly, LARL shows a relatively stable phase relation with the "good" leg leading (whereas in control subjects the arm leads). These two examples (RALL and LARL) demonstrate that the patient can use information from a limb on the "good" side to drive the "bad," perhaps via intact brain or spinal cord structures. In contrast, LALL shows a much less stable phase relation with values that range from large and negative to large and positive. There is also markedly greater variability in the amplitudes of the limb movements.

Figure 3 shows the mean relative phase (left) and the relative phase variability (right) for the patient and control subjects performing in-phase and antiphase movements. Antiphase movements generally were more difficult to make than in-phase movements (in keeping with previous findings[7]). There was a main effect of coordination mode (in-phase vs antiphase) on the variability of relative phase for the control group ($F[1,32] = 153.76$; $p < 0.001$) and the patient ($F[1,8] = 542$; $p < 0.001$). Control subjects found that the RALA condition was the easiest. They found the "diagonal" conditions (RALL and LARL) slightly more difficult than the "same side" conditions (RARL and LALL), although no significant interaction was found between mode of coordination and limb pairing.

The patient was less accurate than control subjects in the phasing of his limbs, with his antiphase performance being predictably worse ($F[1,32] = 27.25$; $p < 0.001$). However, he was most impaired when using only his ipsilesional limbs (LALL). His performance was not markedly different from control subjects in the diagonal conditions and when using only his contralesional limbs (RARL).

Discussion. The most striking result was the patient's marked impairment in ipsilateral interlimb

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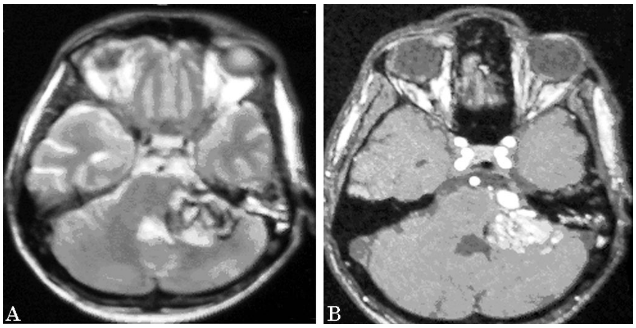

Figure 1. (A) T2-weighted axial MRI of the patient demonstrating an arteriovenous malformation in the left cerebellar hemisphere (anterior lobe and part of the anterior portion of the posterior lobe) and superior peduncle. It is likely that sensory inflow to the left cerebellum is largely intact but that information processing within the anterior medial cerebellum is affected. A recent functional imaging study has demonstrated activity in this region during coordinated bilateral upper limb movements.[10] The superior cerebellar peduncle is also lesioned, thus interrupting the main output to the red nucleus and motor nuclei of the thalamus. (B) Axial MRI with angiographic sequences to illustrate the extent of the abnormal vasculature.

coordination in the LALL condition. His performance was considerably better in the "diagonal" (RALL and LARL) conditions. A traditional explanation in terms of a motor performance deficit cannot account for this pattern of results: his deficit in the LALL condition was much greater than would be expected from

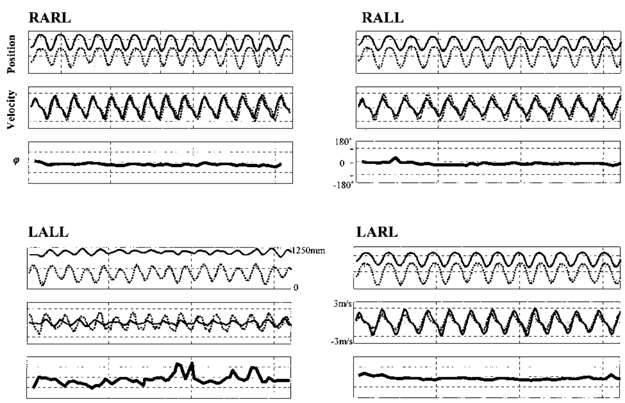

Figure 2. Illustrative single trial data for the patient performing in-phase movement combinations: right arm–right leg (RARL), right arm–left leg (RALL), left arm–left leg (LALL), and left arm–right leg (LARL). In each condition, the top panel shows the positions of arm (solid line) and leg (dotted line); the middle panel shows the velocity of arm and leg; and the bottom line shows the relative phase (ϕ). Kinematic data in the sagittal plane from the wrist (ulnar-triquetrum junction) and ankle (end of the anterior tibiofibular junction) were used in all analyses. Signals were smoothed using a fifth-order Savitzky–Golay polynomial filter (frame size, 79 samples). Phase angles for each limb were calculated as a continuous measure (the inverse tangent of the smoothed velocity over position). Relative phase was computed by subtracting the phase angle of the lagging limb from that of the leading limb.

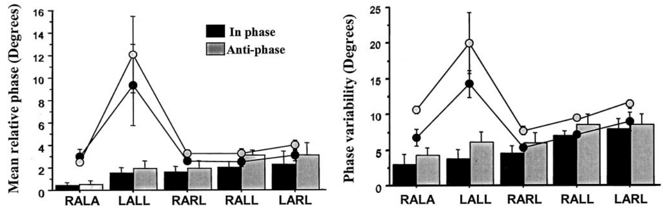

Figure 3. Summary data on two-limb coordination. The left panel shows the mean relative phase for each limb pair condition. In the case of antiphase coordination, it is the difference of the achieved phase from 180°. Mean relative phase is a measure of accuracy of the phase achieved. The right panel shows the relative phase variability. SD of relative phase depicts the stability of the achieved relative phase. Data for the control group are shown in the histograms, and those for the patient are shown in the line plots (filled circles, in phase; clear circles, antiphase).

simple addition of the deficits in using the affected upper and lower limb in the diagonal conditions.

Why then is he so impaired in the LALL condition? We see several potential explanations. First, the cerebellum is implicated in timing.[8] If he is unable to generate accurate timing signals for the left side, then maintenance of an accurate and stable phase relation between the left limbs will be impossible, whereas in the diagonal condition, the right-sided timing signal can support both sides.

Second, modern motor neuroscience research suggests that because of unavoidable delays in sensorimotor transmission and processing, the CNS requires an internal forward model to predict the sensory consequences of actions.[9] Such an internal model depends on sensory information about the current state to predict the future state. If this information is inaccurate (or if the internal model of limb dynamics itself is incorrect[6]), errors will occur. This is likely to be a particular problem for the patient when using both his ipsilesional limbs.

We are currently working to assess the relative contributions of timing and prediction errors to performance impairments.

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