Supplementary material

The statistics of natural movements are reflected in motor errors

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Wavelet phase analysis

To determine the phase relations between movements of the left and right arms as a function of frequency, we performed a Dual-Tree Complex Wavelet Transform (DT-CWT), as described in the Methods of the main text. We generated phase incidence histograms by binning the relative phases into 18 bins each 20° wide. The total incidences across all bins in a given frequency band were then normalized to sum to 1. We validated this analysis on two different datasets. For the first dataset, we generated synthetic left and right elbow angle data by simulating two independent random walks. For the second dataset, we inserted a set of relative time shifts between the left and right elbow angles from the natural movement dataset. In all cases the data was analyzed at low and high frequency bands, as described in the main text. That is, 0.45-0.9 Hz for the low frequency band and 3.2-6.4 Hz for the high frequency band.

Validation using a random walk dataset

The first validation dataset simulated the angular trajectories of the left and right elbows using two independent random walks. Approximately 18 hours of synthetic data was generated by cumulatively summing $8x10^6$ samples (assuming a 120 Hz sampling rate) which were drawn from a zero mean Gaussian distribution with unit variance. The initial 1 second of data is shown in Figure S1.

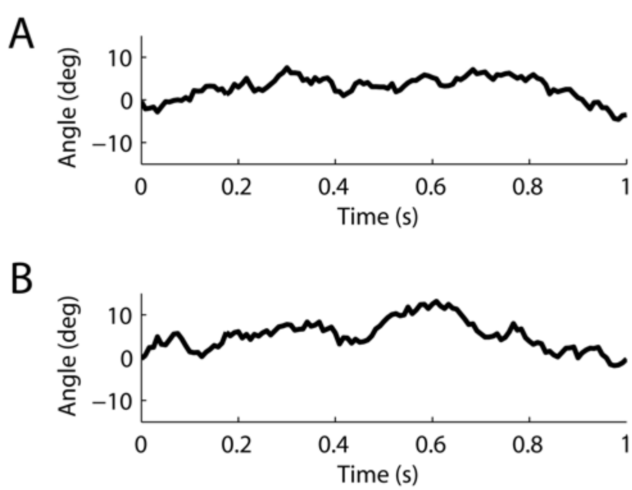

Figure S1. Synthetic random walk elbow angle data for the left (**A)** are right (**B**) elbows.

The wavelet relative phase analysis was run on this dataset and the resulting relative incidence of phase occurrences are shown in Figure S2. It can be seen that the relative incidence of phase is essentially uniformly distributed at both high (Figure S2 A) and low frequencies (Figure S2 B), as expected from two independent random signals.

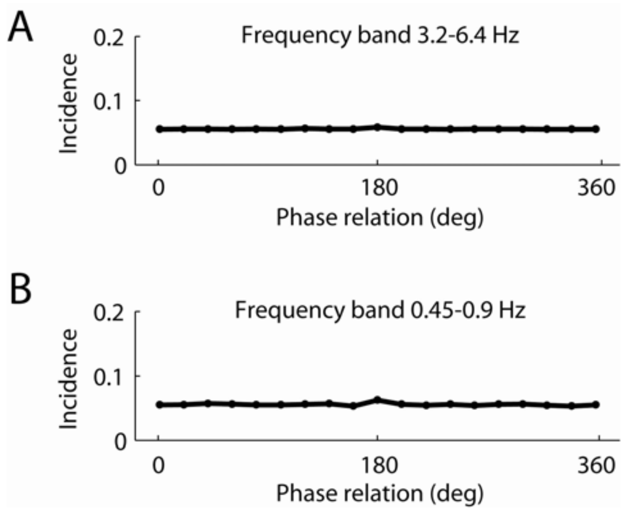

Figure S2 Relative phase analysis for the synthetic random walk dataset. **A** Normalized phase incidences at 3.2-6.4 Hz (high frequency band). **B** Normalized phase incidences at 0.45-0.9 Hz (low frequency band).

Validation using time shifted natural movement dataset

The second validation dataset was generated by introducing a set of time shifts between the left and right elbow angle time series from the natural movement dataset. The effect of such a time shift is to change the phase relations between the left and right datasets in a frequency dependent fashion. We note that only time shifts that lead to small phase shifts (for example, less than 180°) lead to meaningful interpretations. This is because for larger phase shifts, we should expect the phase relationships to tend towards a uniform distribution since the movements of the left and right elbow will no longer correspond to the same action in time.

We selected 6 time shifts which include the two extremes cases of zero (the normal non-shifted case used in the main analysis) and a large time shift of 5 s which, as discussed above, should remove the correspondence between movements of the right and left elbow and result in a uniform distribution of phase relations. The additional time shifts were selected to give rise to specific phase shifts for the high and low frequency bands. Since our phase bins increase in steps of 20°, we then select time delays that would lead to phase shifts that correspond to this bin width.

Two time shifts were selected to correspond to 40° and 80° phase shifts at the low frequency band, as follows. The frequency at the centre of this band is 0.67 Hz, which corresponds to a period of 1.5 s. Therefore, a phase shift of 40° corresponds to a time shift of 0.17 s and a phase shift of 80° corresponds to a time shift of 0.33 s. The two time shifts for the high frequency band were similarly selected to correspond to 40° and 80° phase shifts. The frequency at the centre of this band is 4.78 Hz, which corresponds to a period of 0.21 s. Therefore, a phase shift of 40° corresponds to a time shift of 0.023 s and a phase shift of 80° corresponds to a time shift of 0.047 s.

The wavelet relative phase analysis was run on the time-shifted datasets for the 6 time-shift values and across the 6 subjects. The results are shown if Figure S3. At the large time shift of 5 s, the phase relation at both low and high frequencies was uniform (Figure S3 A and F). This is to be expected because at such a large time shift, movements of left and right elbows will be unrelated. For time shifts corresponding to an 80° phase shift, it can be seen that the peak in incidence that occurs at 0° in the non-shifted data, has been shifted towards 80°, for both the low (Figure S3 B) and high frequency bands (Figure S3 G). A similar effect occurs for time shifts corresponding to a 40° phase shift (Figure S3 C and H). For comparison the zero time shift incidences are shown (Figure S3 D and I). Finally, results for the 40° and 80° phase shifts for the low and high frequency bands were aligned by shifting each curve by its expected phase shift and overlaying on the original non-shifted analysis (Figures S3 E and J). It can be seen that there is a good agreement between these curves, indicating that the relative time shifts have resulted in the expected phase shifts.

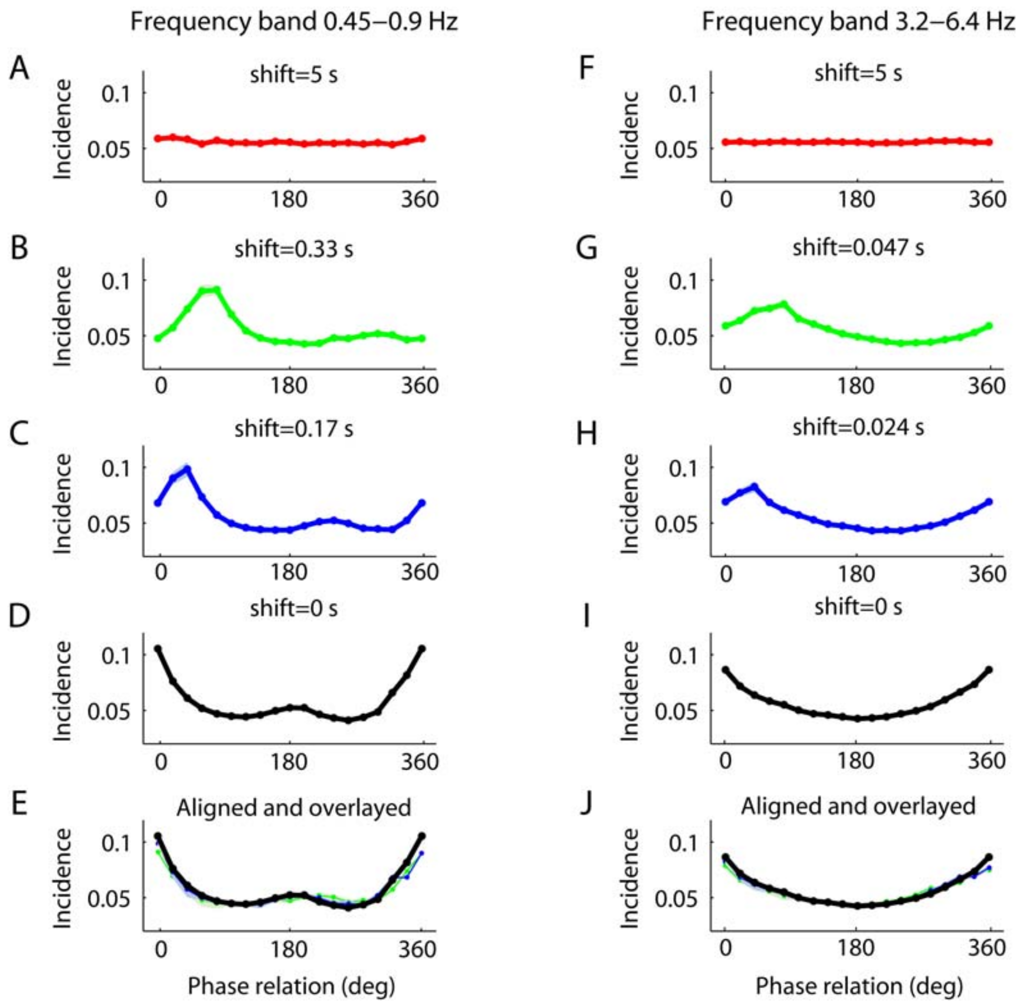

Figure S3 Validation of wavelet phase analysis with a dataset generated by inserting a relative time shift between the left and right elbow angle data from the natural movement dataset, averaged over all six subjects. **A-E** Relative phase incident at 0.45-0.9 Hz (low frequency band). **F-J** Relative phase incident at 3.2-6.4 Hz (high frequency band) **A & E** For a large time shift (5 s), relative phase incidence is uniform. **B & G** A time shift corresponding to 80° results in the expected phase shift (see text for details). **C & H** A time shift corresponding to 40° results in the expected phase shift (see text for details). **D & I** The relative phase incidences for zero time shift. **E & J** Good agreement of curves is obtained when the relative phase incidences for different time shifts are aligned and overlaid with the zero time shift data.

Conclusions

To summarize, analysis of a random walk dataset yielded a uniform phase incidence and inserting various relative time shifts in the natural movement dataset resulted in the expected shifts relative phase incidence. These two experiments thus demonstrate the validity of the wavelet phase analysis that was used in the analysis of the natural movement dataset described in the main text.