Topological Similarity of Motor Coordination in Rhythmic Movements

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Background: Physical properties have been assumed to be motor representations, but an alternative has been explored.

Approach: A computational-theory-level account for motor representation is proposed based on a dynamical system theory for multiple-body-parts coordination.

Results: Analysis on a class of complex rhythmic movements revealed invariant nature of attractors of bodily movements across different physical conditions.

Suggestion: A set of invariant properties of bodily movements as a dynamical system has preferable computational properties, and may be central attributes in computation of complex motor coordination.

Background

How bodily movements are to be represented?

- To provide information to peers about surrounding environment
- Elicit complementary and similar emotions
- To be an incentive promoting social relationship

Inverse computation for ill-posed problem (Kawato, 1991)

- **Marrian computational theory**: motor control as optimal estimation for ill-posed problem
- **Kinematic optimization (Flush & Hogan, 1985)**
- **Dynamic optimization (Uno & Kawato, 1989; Wolpart, Doya, Kawato, 2003)**

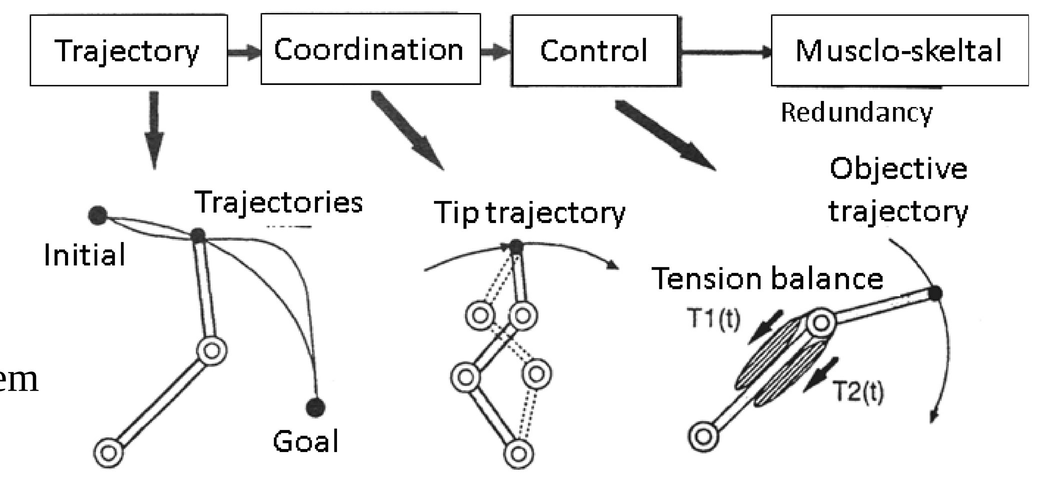

Fig1. Ill-posed problems in motor control (Kawato, 1996)

Problems: scaling-up for whole-body?

- A model for relatively simple movements (e.g., reaching)
- Too large computation for multi-body complex movements
- Large potential cost in learning motor control
- Difficulty in cross-modal generalization

Computational framework: Dynamical invariants as a motor representation

Hypothesis:

- Movements reflect a dynamical system in a high-dim. state space of neuro-body-environment (Turvey, 1998)
- Quantities invariant to coordinates characterize topological nature of the trajectories (e.g., attractor dimension, Lyapunov exponent, and etc. (Kanz & Schreiber, 1997))
- They abstract over physical particulars such as distance speed, etc.
- ***generating partitions:*** best encoding systems of a nonlinear dynamical system.

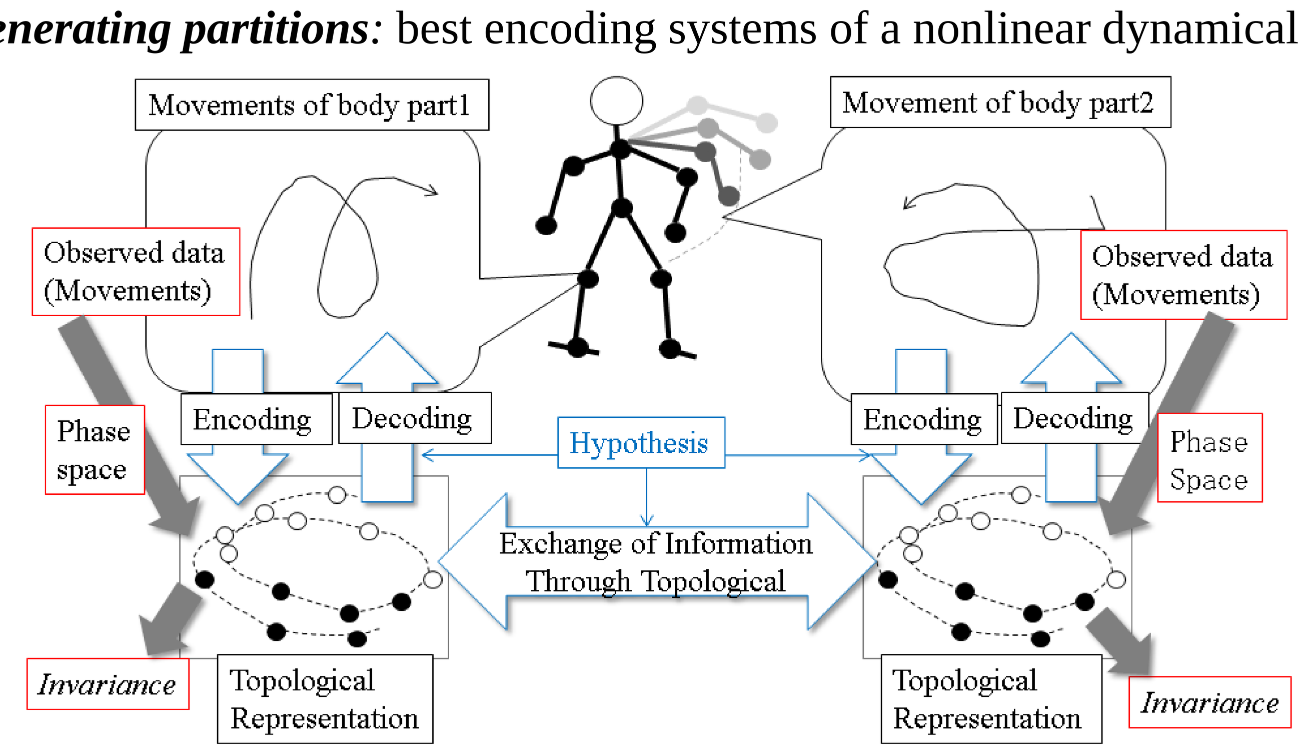

Fig2. Motor coordination through dynamical invariances.

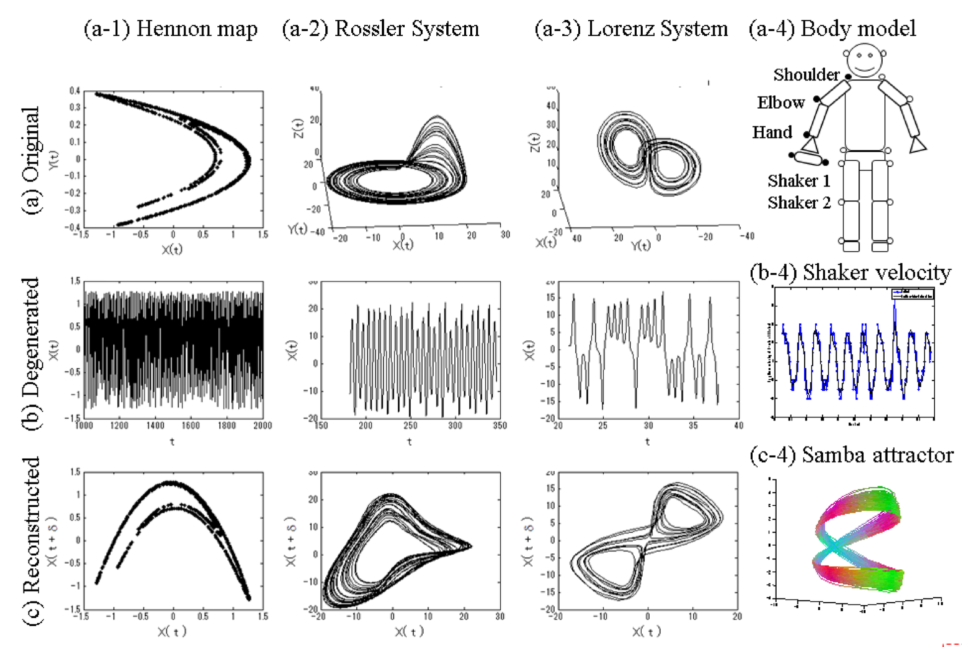

Fig 3. Phase space of (a-1) the Hennon map, (a-2) the Rossler system, (a-3) Lorenz System, and (a-4) the body model and attached markers. (b1-4) A univariate time series from the original phase space in (a1-4). (c1-4) The reconstructed phase space from the low dimensional observed time series in (b1-4).

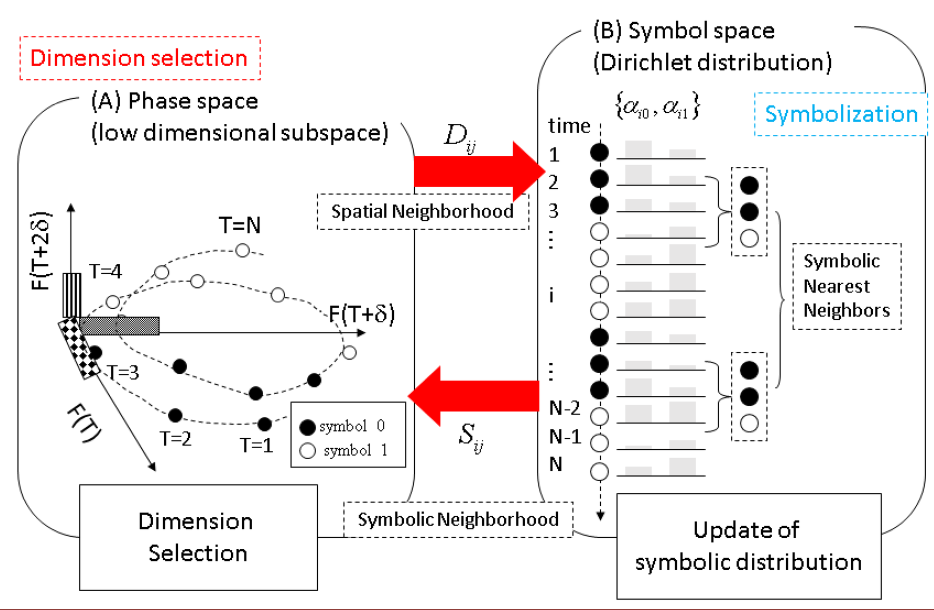

Fig 4. Estimation of generating partitions through multivariate time series (Buhl & Kennel, 2005; Hidaka & Yu. 2010)

Algorithm:

1. Initialize parameters (symbol series and weights on dimensions)
2. It estimates a tentative partition giving the symbol series by optimization.
3. Once a better symbol series is given, it selects subset of phase space
4. Back to 2. until it satisfies

Behavioral study: Complex Rhythmic Movements by Skilled Performers

- **Subjects**: 5 subjects were asked to shake an music instrument to a samba rhythm at a given tempo.
- **Data**: 3D movements of 18 markers attached on body parts and music instrument are recorded 86Hz for 97.4 second.
- **Analysis:** Applying the local linear projective method, the phase space reconstruction of each time series on the 31 dimensional time delay space with 46 msec (i.e., { t, t + Δt, t + 2Δt, . . . , t + 30Δt } where Δt = 46 msec) (Takens, 1981).

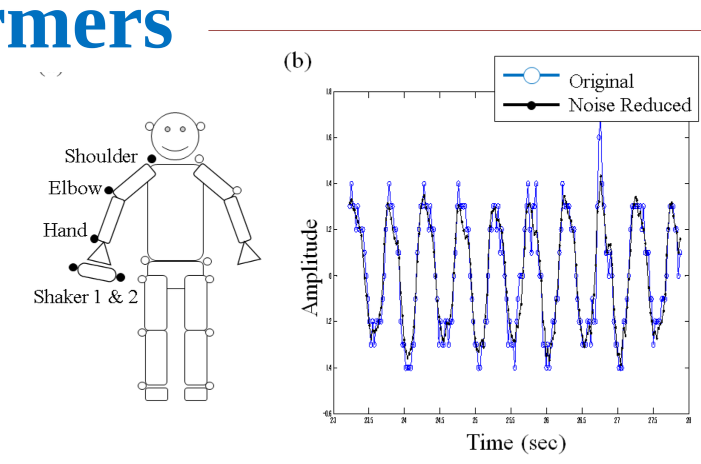

Fig 5. (a) Sensor locations & (b) A raw time series

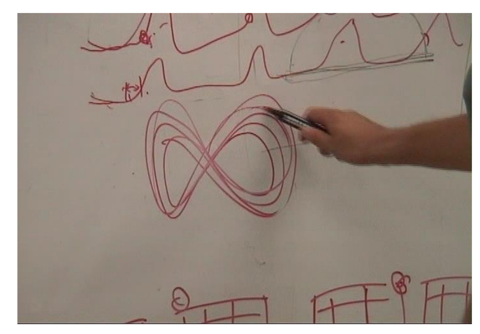

Fig 6. Hand-write mental image of Samba rhythm by an expert

Results & Discussion

- A set of velocity data cannot capture the similarity of movements across subjects (Fig. 7).
- Dynamical invariance capture the similarity across subjects and across tempo conditions (Fig. 9).
- Trajectory in a high dimensional phase space (Fig 8.) show similarity to the mental image of the samba rhythm (Fig. 6).

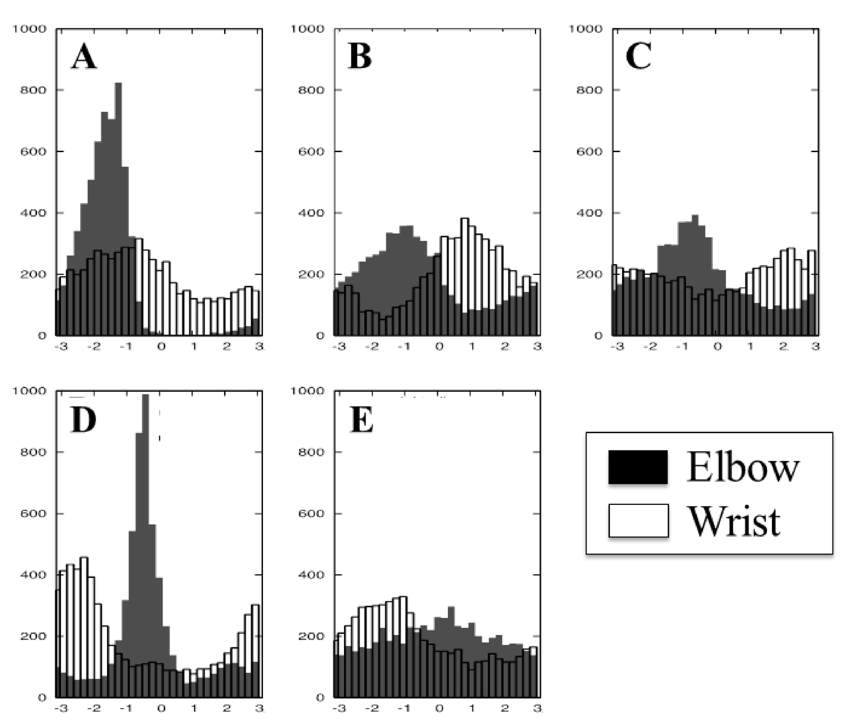

Fig 7. The distribution of phase shift (radian) of right elbow (gray) and right wrist (white).

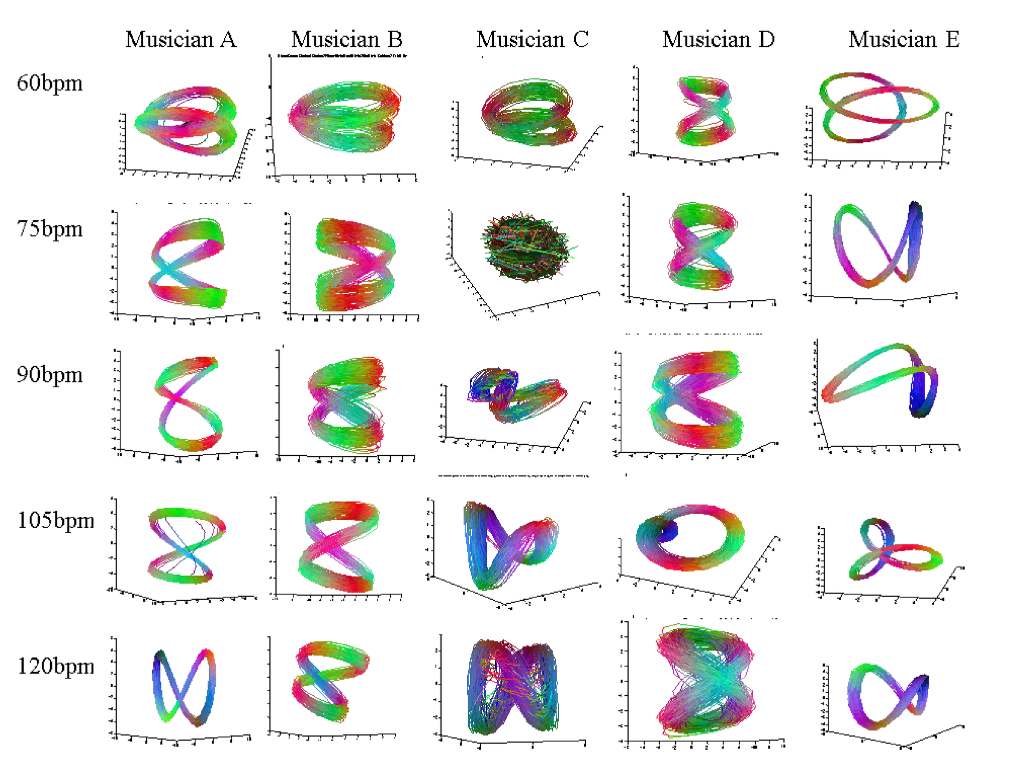

Fig 8. The reconstructed phase space embedding in three dimensional time delay space in Musician A-E playing at tempo 60, 75, 90, 105, and 120 BPM.

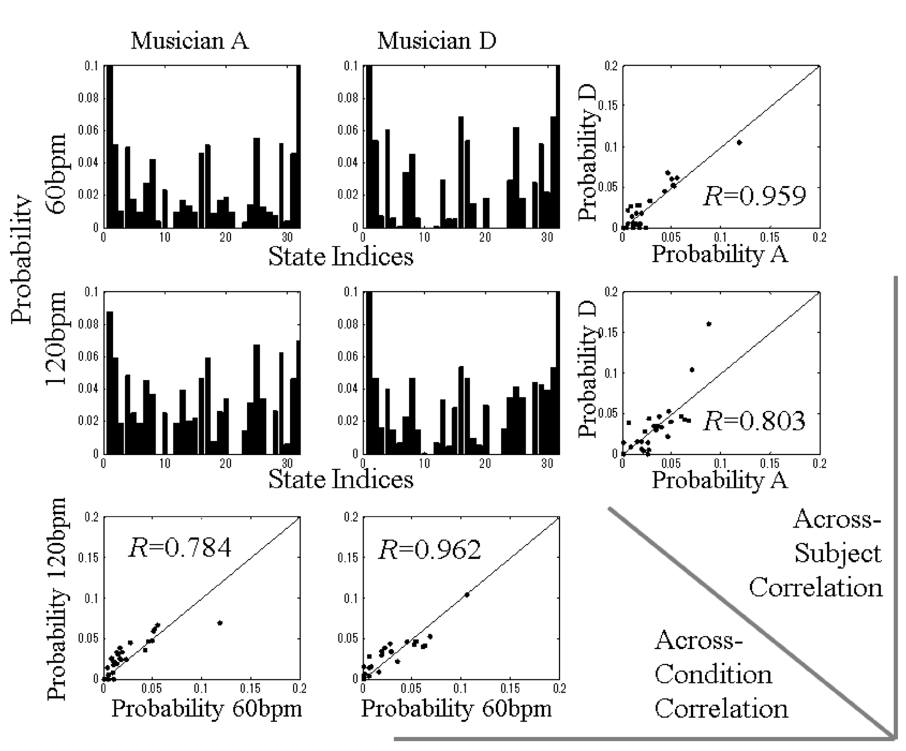

Fig 9. Topological similarity across subjects and tempo conditions.Stationary distributions of states in each of symbolic dynamics

Conclusions

Results: Successful characterization of similarity in complex rhythmic movements by dynamical invariances.

Implication: A set of invariant properties of bodily movements as a dynamical system has preferable computational properties, and may be central attributes in computation of complex motor coordination

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