Characterizing task-specific motor variability in human skilled movements as dynamical invariants: a case study

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Abstract. Human body is at the center of our day-to-day activities. To reveal bodily skills hidden in our daily life, we need to understand how our central nervous system manipulates our body. Ones hypothesized that the motor variability of our skilled movements is constrained to task-irrelevant subspace. This hypothesis predicts that human skilled movements show small variability in trajectory, where the variability is critical in task performance. We attempted to test this prediction by characterizing human bodily movements regarded as those generated by a dynamical system. The results of our analysis matched this prediction: the motor variability in trajectory, or the degrees-of-freedom, reduces near the 'critical point' of motion regarding the task.

Keywords: skilled movement, motor variability, dynamical systems

1 Introduction

Human body is at the center of our day-to-day activities. Even a simple daily task, e.g., using chopsticks, the movements of our body parts are well organized and coordinated. Craftsmen are people who have elaborated use of their own body for their special task. Motor control system (including central nervous system) that produce movements solving their task flexibly is described as skilled. Nikolai Bernstein in 1940s [1] saw a source of flexibility of our bodily movements in our body's large number of degrees-of-freedom, or motor redundancy: one can achieve the same goal in multiple body coordinations. Among multiple body coordinations, how does our motor control system choose one out of many?

An attempt for this question is by identifying underlying principles of motor control from observed or realized skilled movements for some task. The research groups of optimal feedback control and experimental neuroscience hypothesized that the optimal motor control strategy permits motor variability in movements along task-irrelevant dimensions larger than task-relevant dimensions [7, 8]; Or equivalently, motor variability in movements is constrained to redundant subspace (uncontrolled manifold) [6, 4]. The hypothesis [7, 8, 6, 4] is illustrated in Figure 1 that depicts two kinds of trajectories of some body part (e.g., one hand) produced by well-skilled and less-skilled motor control systems. Their difference may be clear in details, when observing how a trajectory of repeated movements pass through a flat section. The hypothesis states that (a) well-skilled motor control systems constrain motor variability in movements along some task-irrelevant subspace but (b) less-skilled ones cannot constrain and so produce movements undirectedly variable in a (relatively) larger subspace. The key idea of the hypothesis is that the motor control system organizes our movements in order to minimize the task error, and resulting skilled movements show small motor variability where even small variability is critical in task performance.

Testing this hypothesis involves some difficulties in determining such task-relevant and task-irrelevant subspace [5]. In this paper, we view human body as a dynamical system. A trajectory of differentiable dynamical systems preserves the invariant, 'fractal dimension', under smooth transformations. A sort of fractal dimension characterizes the degrees-of-freedom or spatial variability at each point [2]. Thus, by studying such a dynamical invariant, we can confirm the hypothesis regarding skilled motor control systems via their produced movements: the skilled motor control system can be characterized by the dynamical invariant, 'dimension', as well-skilled movements have smaller dimensional than less-skilled ones.

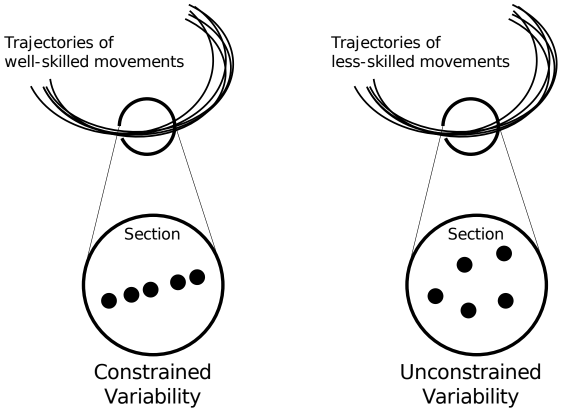


Fig. 1. Task-constrained motor variability. If the motor control system is well-skilled, motor variability is constrained to task-irrelevant subspace (the points can vary only along the 'line'). Unless (less-skilled), motor variability is not constrained to some specific subspace (the points can vary on the 'surface').

2 Experiment: setup and data

We human use primarily our dominant arm (hand) in our daily works, especially when accuracy in movements is needed (i.e., handedness). In this sense, our dominant arm (hand) can be well-skilled. On the other hand, our non-dominant arm (hand) can be less-skilled in our daily works. To test the hypothesis [7, 8, 6, 4] in human movements, our experiment consists of comparison between bodily movements using the dominant (well-skilled) arm versus non-dominant (less-skilled) arm of each subject. By comparing between dominant and non-dominant arms within subjects, the side-effects arising from differences between subjects, i.e., not motor control systems but physical and psychological factors, can be reduced.

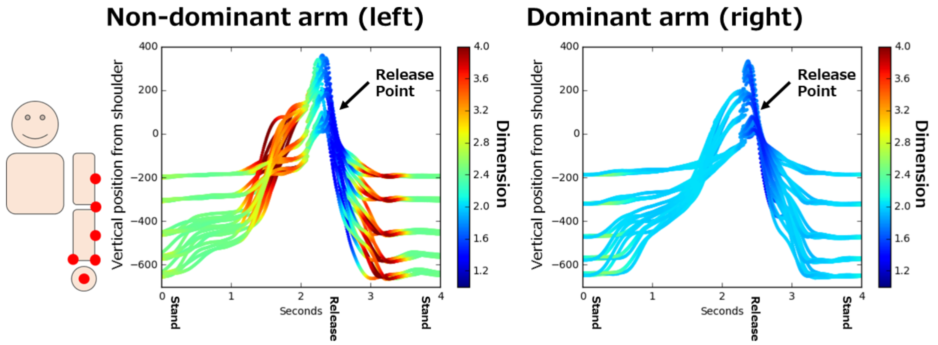
The task adopted in this case study should satisfy the two requirements: (1) The task is usually done by the dominant arm but not by the non-dominant arm; (2) Even less trained, the task can be done by the non-dominant arm. 'Throwing-a-ball' is a motion satisfying these requirements, because (1) The dominant arm can be used because it needs accuracy in movements; (2) It is simple enough. For this 'throw-a-ball' task, the most critical point in motion can be about the release point. Based on the hypothesis [7, 8, 6, 4], we predict that this critical point (or release point) can be characterized by the dynamical invariant from the produced movements.

We recorded 'throw-a-ball' motion using the 3D optical motion capture technology of Vicon Motion Systems (8 infrared cameras; each 120 Hz) in our university. Subjects wore the body suit with 39 reflective markers (the plug-in gait marker placement [9] was used). Each subject performed first 5 trials with the dominant arm and next 5 trials with the non-dominant arm (throw a ball 5 times by each arm) successively. No specific target point was instructed. We recorded 4 subjects (3 males and 1 female; between 30–40-year-olds). One of them was a trained handball player in high-school. Another of them has less experience in sports. We analyzed these contrastive two subjects in this case study.

3 Results

To characterize motor control systems between the dominant and non-dominant arms throwing a ball, we focused the data of our analysis on the markers on both arms (6 markers) and shoulders (1 marker). Relative coordinates of the arm markers from the shoulder marker were analyzed to estimate the fractal dimensions. The point-wise fractal dimension estimation method was developed by [3]. For the results below, we used a time-delay embedding of length 10 (we obtained quantitatively similar results for other parameters). Depending on the recording quality of data, some of markers on the hands or wrists were ignored (see below).

First, the movements of the subject who was a trained handball player were analyzed. Figure 2 shows the 5 trajectories of 5 markers on each arm. The subject showed the upright standing posture for the first and last a few moments of each trial. The 5 trajectories (per each trial) were aligned at the times one of these markers reached the highest position. Immediately after these times, the subject released the ball (the release point in the figure). The colors of the points in Figure 2 indicate the estimated fractal dimensions of the points. The dimensions of this subject's movements got relatively smaller around the release point. This result suggests that the motor control of this subject achieved small motor variability around releasing the ball. The result matched our prediction that, in the throw-a-ball task, the dynamical invariant detects the most critical point that is the release point. This observation is common in both the dominant and non-dominant conditions. By comparing the estimated dimensions between the conditions, it suggests that generally the non-dominant arm movements have larger fractal dimensions. In other words, the non-dominant or less-skilled arm shows larger motor variability than the dominant or well-skilled arm.


Non-dominant arm (left)

Dominant arm (right)

Fig. 2. Trajectories of the subject who was a trained handball player. The colors indicate motor variability characterized by fractal dimensions.

The same procedure of analysis was applied to the other subject who has less experience in sports. Figure 3 shows 5 trajectories of 4 to 6 markers on each arm. These trajectories were aligned in the same way. The colors of the points indicate the fractal dimensions. Similarly to the previous subject, the fractal dimensions of the movements come to smaller around releasing of the ball. That is, this subject's motor control achieved smaller motor variability; but it is not so clear unlike the previous trained subject. When comparing between the conditions, again, the dimensions of the movements by the non-dominant, less-skilled arm were generally larger than the dominant, well-skilled one.

4 Discussion

Within 'throw-a-ball' task, we examined the hypothesis [7, 8, 6, 4] (illustrated in Figure 1) that states (a) well-skilled motor systems constrain motor variability in movements along some task-irrelevant subspace but (b) less-skilled ones cannot constrain and so produce movements undirectedly variable in a (relatively) larger subspace. This was confirmed by our analysis that the dynamical invariant, 'fractal dimension', of well-skilled movements have smaller dimensional than less-skilled ones. Regardless of which arm the subjects use to throw a ball, the

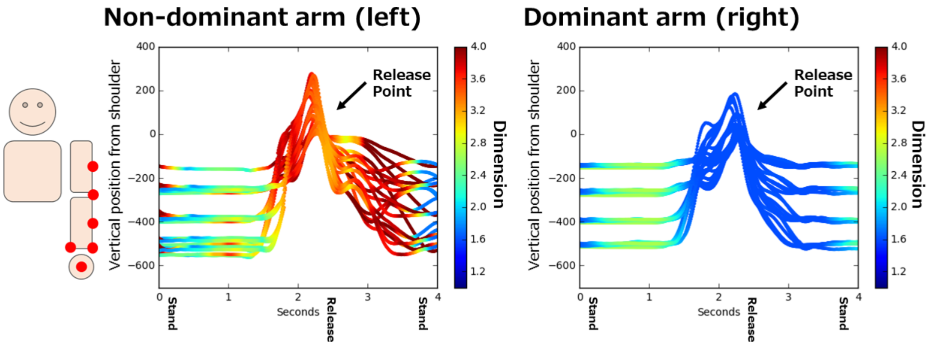


Fig. 3. Trajectories of the subject who has less experience in sports. The colors indicate motor variability characterized by fractal dimensions.

fractal dimensions got smaller around releasing a ball (the release point), which seems to be the critical point in this throw-a-ball task.

Our dominant vs non-dominant comparison seems to work well. The advantage of this experimental design is that the same brain is used to produce movements in both dominant and non-dominant conditions. This does not mean the subject uses in the exactly same way the motor control system; but we think that typically the ways of use of motor control systems within subject could be more similar than those between subjects. If this is true for a task, this paradigm works better to study bodily skills in our daily activities.

In this case study, we analyzed a subset of our full data: only the markers including arms and shoulders. (deleted) Other body segments could take each significant role in this task. We will develop the way to treat multiple body segments, each having different functions toward the same task. To understand how skilled movements are produced by coordinating our entire body, our future works include adding more subjects and developing such techniques. Automatically identifying the subset of mostly task-relevant body segments is a important research topic from the view-point of skill inheritance among craftsmen (how people can).

5 Conclusion

By characterizing the throw-a-ball movements of human subjects by a dynamical invariant, we confirmed the hypothesis that states motor variability is constrained by the task error. By comparing the dominant arm vs the non-dominant arm conditions in the throw-a-ball task, the skilled movements show smaller motor variability near the release point. This result suggests an advantage of this dominant vs non-dominant experimental paradigm for understanding bodily skills in our daily activities.

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