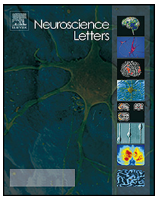
Neuroscience Letters 577 (2014) 38–44

Contents lists available at ScienceDirect

Neuroscience Letters

journal homepage: www.elsevier.com/locate/neulet



Extraction of practice-dependent and practice-independent finger movement patterns

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HIGHLIGHTS

- Little is understood about reorganization of hand movements through practice.
- Non-musicians performed piano practice over four days.
- Hand kinematics was measured using a motion capture system.
- Principal component analysis determined practice-dependent movement reorganization.
- The reorganization was characterized by enhancement of individuated finger movements.

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form 15 May 2014
Accepted 6 June 2014
Available online 13 June 2014

Keywords:
Multivariate analysis
Motor learning
Motor redundancy
Motor skill acquisition

ABSTRACT

Extensive motor practice can reorganize movements of a redundant number of degrees of freedom (DOFs). Using principal component (PC) analysis, the present study characterized the movement reorganization of the hand that possesses a large number of DOFs during a course of practice. Five musically naïve individuals practiced to play a short sequence of melody with the left hand for four successive days, and their hand kinematics was measured using a motion capture system. The PC analysis of the hand joint kinematics identified two distinct patterns of movement, which accounted for more than 80% of the total variance of movements. The second PC but not the first PC changed through practice. A correlation analysis demonstrated that the PC sensitive to the practice was characterized by coupled movements across fingers in the same direction. A regression analysis identified a decrease in the contribution of this PC to the hand movement organization through practice, which indicates a reduction of the movement covariation across fingers and thus an enhancement of the individuated finger movements. The results implicate potential of PC analysis to extract practice-invariant and practice-dependent movement patterns distinctively in complex hand motor behaviors.

1. Introduction

Extensive motor practice reorganizes movements at multiple degrees of freedom (DOFs) so as to optimize motor performance. Previous studies have extensively investigated the effects of practice on multi-joint movements of the upper and lower extremities [11,14,16,22]. For example, learning to play the violin was characterized by a suppression of shoulder motion while maintaining elbow motion, which improved movement accuracy [14]. The temporal coordination between the shoulder and elbow was also changed through practicing the batting motion so as to rotate the shoulder and elbow in a proximal-to-distal order, which resulted in an improved maximum speed of movement [22]. Compared with the upper and lower extremities, the hand possesses a larger number of DOFs. However, little is known about the practice-related movement reorganization.

Hand dexterity is a key motor skill that enables proficient tool use, such as grasping [18,19], typing [21], and musical performance [1,3,4,9]. Previous studies have characterized the movement organization of multiple joints of the hand using various multivariate analyses [4,7,8,18,19,21,23]. For example, principal component (PC) analysis decomposed hand motion during grasping objects of various sizes and shapes into two fundamental patterns of finger joint coordination [19]. Similarly, hand kinematics during piano performance consisted of two or three movement patterns [4]. Therefore, it is likely that multivariate analyses can serve as

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http://dx.doi.org/10.1016/j.neulet.2014.06.012

an effective means of extracting fundamental patterns of movement organization across fingers and joints of the hand. However, when characterizing movements that evolve through practice, an increase in dimensionality limits a conventional use of multivariate analysis that identifies movement covariance across joints. Furthermore, the strong constraints at both the biomechanical and neurophysiological levels, being unique features of the hand [20], can prevent specific movement elements from changing with practice, which can make it difficult to identify movement features sensitive to practice. Using a novel way of PC analysis, the present study challenged for extracting individual movement patterns that change and remain through a course of practice separately. To this end, musically naïve individuals were asked to practice a short sequence of piano melody for four successive days, and their hand kinematics were measured using a motion capture system. Based on the previous findings of the superior independence of movements across fingers for more skilled pianists [4], we postulated that a practice-variant movement pattern plays a role in facilitating the individuated finger movements.

2. Material and methods

2.1. Participants

Five musically naïve right-handed male individuals (age: 21–24 yrs) participated in the experiment. None of the participants had formal education in playing musical instruments prior to the experiment. The experimental protocol was approved by the local ethics board of Kwansei Gakuin University, and the participants provided informed consent prior to the experiment. The experiment was performed according to the Declaration of Helsinki.

2.2. Experimental task

The current experiment includes 50 practice trials per day for 4 successive days (200 trials in total). During the practice, each participant played a certain tone sequence consisting of 12 strokes with a predetermined fingering using the left hand (i.e., a sequence of "CDCECFDEDFEF" with the fingering of "545352434232"; 2: Index, 3: Middle, 4: Ring, 5: Little). Each participant played a digital piano (YAMAHA, P-250) with an inter-keystroke interval (IKI) of 500 ms in synchronization with a metronome (2 strokes per second) at a predetermined loudness (*mezzo-forte*, 90 MIDI velocity). This task was repeated 50 times per day, and the trials that included erroneous stroke(s) and/or stronger or softer stroke(s) (±5 MIDI velocity) were discarded and repeated. Data were measured at the first 5 ("*pre-session*") and last 5 ("*post-session*") trials at each of the 4 successive days (i.e., eight sessions in total).

Before starting the experiment, each participant was asked to practice to familiarize themselves with both the given tone sequence and the piano based on instructions from the experimenter. This familiarization session took approximately 5 min, during which the participants memorized the sequence and fingering.

2.3. Data recording and analysis

During the experiment, MIDI data that include the time at which each key was depressed and released were collected from the piano with a time resolution of 1 ms. The kinematic data were time-normalized so that each inter-keystroke interval became 100.

Twenty-six spherical reflective markers were placed on the participants' hand to determine anatomical landmarks. These markers were put on the skin over the fingertips and on the 3 joint centers of all 5 digits, the proximal ends of the metacarpal bones and the distal ends of the radius and ulna. The motion of the reflective markers was recorded at 120 Hz using 13 high-speed cameras surrounding the piano. The camera locations were carefully arranged so that the position data of all the markers would be recorded while the target task was performed. The spatial resolution in the camera setting was 1 mm. The 3D time-position data of each marker were obtained using a direct linear transformation method. All the procedures were established in our previous study [5]. The position data were digitally smoothed at a low-pass cutoff frequency of 10 Hz using a second-order Butterworth digital filter.

2.3.1. Definition of joint angle

Using the position data of the individual markers in a three-dimensional space, the angles at the metacarpophalangeal (MCP), proximal-interphalangeal (PIP), and distal-interphalangeal (DIP) joints for flexion and extension were computed at the index, middle, ring, and little fingers. The flexion/extension angle of the PIP and DIP joints, each of which has only one degree of freedom, can be computed as an inner product. To compute the angle of the MCP joint of a certain finger, we used position data that consisted of four markers, including the proximal ends of this finger and its adjacent finger(s) and the centers of the MCP and PIP joints of this finger. Point X was defined as a foot of a perpendicular from point P to the plane α that contains the points A, B, and C. The angle formed by vectors $\overrightarrow{AX}$ and $\overrightarrow{AP}$ was defined as θ. Point X is on the plane containing points A, B, and C, which yields the following equations.

$$\overrightarrow{PX} = r\overrightarrow{PA} + s\overrightarrow{PD} + t\overrightarrow{PCX} \tag{1}$$

$$r + s + t = 1 \tag{2}$$

Then, the following equations hold true because PX is orthogonal to α.

$$\overrightarrow{PX} \cdot \overrightarrow{AB} = 0 \tag{3}$$

$$\overrightarrow{PX} \cdot \overrightarrow{AC} = 0 \tag{4}$$

Because points A, B, and C are observational data, $\overrightarrow{PX}$ can be evaluated using Eqs. (1)–(4). Then, vector $\overrightarrow{AX}$ was evaluated as follows.

$$\overrightarrow{AX} = \overline{-PA} + \overrightarrow{PX}$$

Thus, the MCP joint angle formed by $\overrightarrow{AX}$ and $\overrightarrow{AP}$ (i.e., θ) was evaluated by the following equation.

$$\theta = \arccos\left(\frac{\overrightarrow{AP} \cdot \overrightarrow{AX}}{|\overrightarrow{AP}| \cdot |\overrightarrow{AX}|}\right) \times \frac{180}{\pi}$$

It is anatomically possible that the MCP joint hyper-extends and thus that the value of θ exceeds π. Therefore, depending on the positional relationship between points P and X, the MCP joint angle was evaluated as follows:

$$\theta_{\mathrm{MCP}} = \begin{cases} \pi + \theta & \mathrm{P}y > \mathrm{X}y \\ \pi - \theta & \mathrm{P}y < \mathrm{X}y \\ \pi + \theta & \mathrm{P}y = \mathrm{X}y \end{cases}$$

where Py and Xy indicate the y-coordinate of points P and X, respectively.

2.3.2. Principal component analysis

To characterize changes in the patterns of hand movement kinematics among various DOFs at the hand over the 4 days of practice, we performed PC analysis. The PC analysis identified patterns of covariation of the time-varying joint kinematics across the practice sessions. The input to the PC analysis was the averaged joint angular velocity for each session. Each of the 8 practice session vectors consisted of a series of 12 joint velocity waveforms (3 joints × 4 fingers). As opposed to the previous method that extracts movement covariance across joints [19], the current study uses an input