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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.

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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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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 $\overrightarrow{\mathrm{AX}}$ and $\overrightarrow{\mathrm{AP}}$ was defined as θ. Point X is on the plane containing points A, B, and C, which yields the following equations.

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

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

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

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

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

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

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

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

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

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

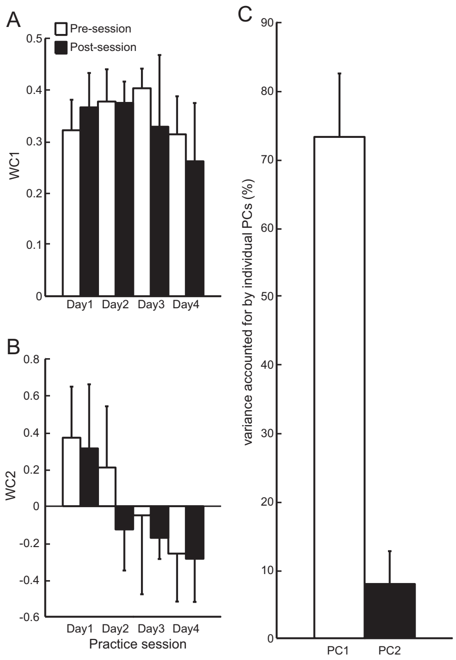

Fig. 1. Results of PC analysis. (A and B) Group means of the weighting coefficients over four days of practice (=eight practice sessions) for PC1 and PC2. (C) A group mean of the variance accounted for by the first two PCs. An error bar indicates a standard deviation across the participants.

matrix that consists of the practice session and a series of angular velocity waveforms of all the joints, and this allowed the covariance of movements across sessions to be computed. We conducted a separate analysis for each of the five participants.

The PC analysis in the present study results in n basic PC waveforms, which are computed from the $n \times n$ covariance matrix of the n practice-session vectors ($n = 8$). The covariance calculation removes the mean from each of the n columns of the input matrix. Thus, the angular velocity waveforms at each joint for each practice session could be perfectly reconstructed as the average angular velocity at the jth joint for the ith practice session (mean $\dot{\theta}_i^j$) plus a weighted sum of the n PC waveforms ($PC^j{}_{1\ldots n}$) at the jth joint:

$$\dot{\theta}_i^j = \text{mean}\ \ \dot{\theta}_i^j + PC1^j \times W1_i + \cdots + PCn^j \times Wn_i$$

where $W1_i$–Wn_i are the weighting coefficients (WC) for the ith practice session. The PCs are ranked such that PC1 accounts for the largest portion of the variance. We then quantitatively determined the correspondence of PCs across the pianists based on the technique that we used previously [4,7].

2.3.3. *Correlation analysis*

To assess the independence of movements across fingers at the individual PC waveforms, a correlation coefficient of the time-varying joint motion was computed between the finger used for the keystroke ("striking finger") and one of the other 3 fingers ("non-striking finger"). For each of the 4 fingers, the coefficient was computed during the period from one previous strike to one following strike with the target finger (=3 successive strikes). Because each trial included 3 strikes with each of the fingers, the coefficient was computed for each of the 3 strikes and then averaged. This value was averaged across the first 5 trials ("*pre-session*") and across the final 5 trials ("*post-session*") for each of the 4 days. The correlation coefficient between the striking and non-striking fingers was computed at each of the MCP, PIP, and DIP joints for each participant.

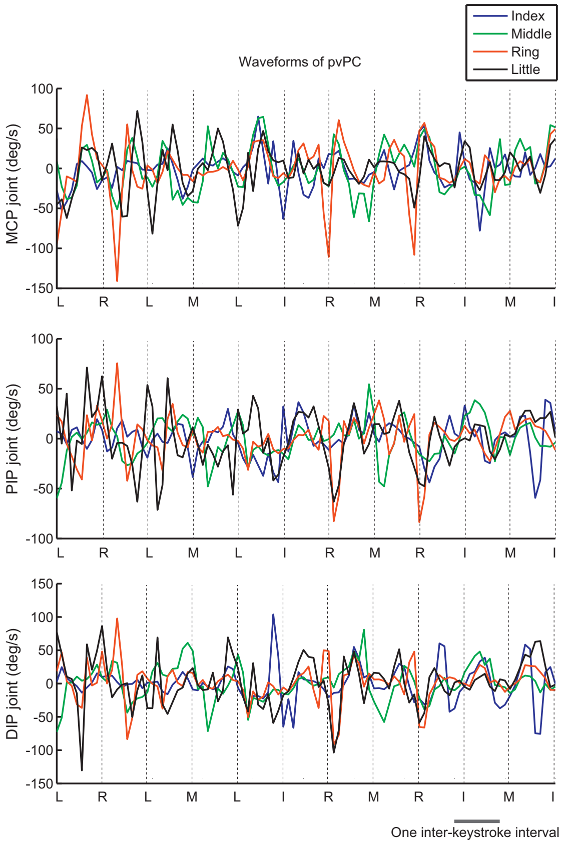

Fig. 2. Time-varying waveforms of the joint angular velocity of the pvPC (i.e., PC2) for the index (blue), middle (green), ring (red), and little (black) fingers at the MCP (top panel), PIP (middle panel), and DIP (low panel) joints in one representative participant. Flexion and extension correspond to negative and positive values, respectively. *X* axis: time normalized by each inter-keystroke interval. I, M, R, and L indicate a moment of keystroke with the index, middle, ring, and little fingers, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2.4. *Statistics*

To statistically evaluate the change in the WC over the practice sessions, we used a one-way repeated-measures analysis of variance (ANOVA) with the "practice session" (within variable, 8 levels) as the independent variable and Tukey post-hoc tests for multiple comparisons. A statistical analysis was performed using R (ver. 3.0.2).

3. Results

Fig. 1 illustrates the group means of the weighting coefficient at the 8 practice sessions (pre/post × 4 days) for the first and second PCs. The weighting coefficient of PC1 was constant across the practice sessions (Fig. 1A). The one-way ANOVA with repeated measure showed no significant main effect ($F(7,28) = 1.42$, $p = 0.235$, eta-squared = 0.26). By contrast, the weighting coefficient of PC2 decreased across the sessions (Fig. 1B). The ANOVA yielded a significant main effect of session ($F(7,28) = 3.67$, $p = 0.006$, eta-squared = 0.48). A post-hoc test revealed smaller weighting coefficients of both the pre- and post-sessions on day 4 compared to the pre- and post-sessions on day 1. The results indicate that PC2 but not PC1 represents a finger movement pattern that varied in relation to practice. In the following section, we refer to PC1 as the practice-invariant PC (piPC) and PC2 as the practice-variant PC (pvPC).

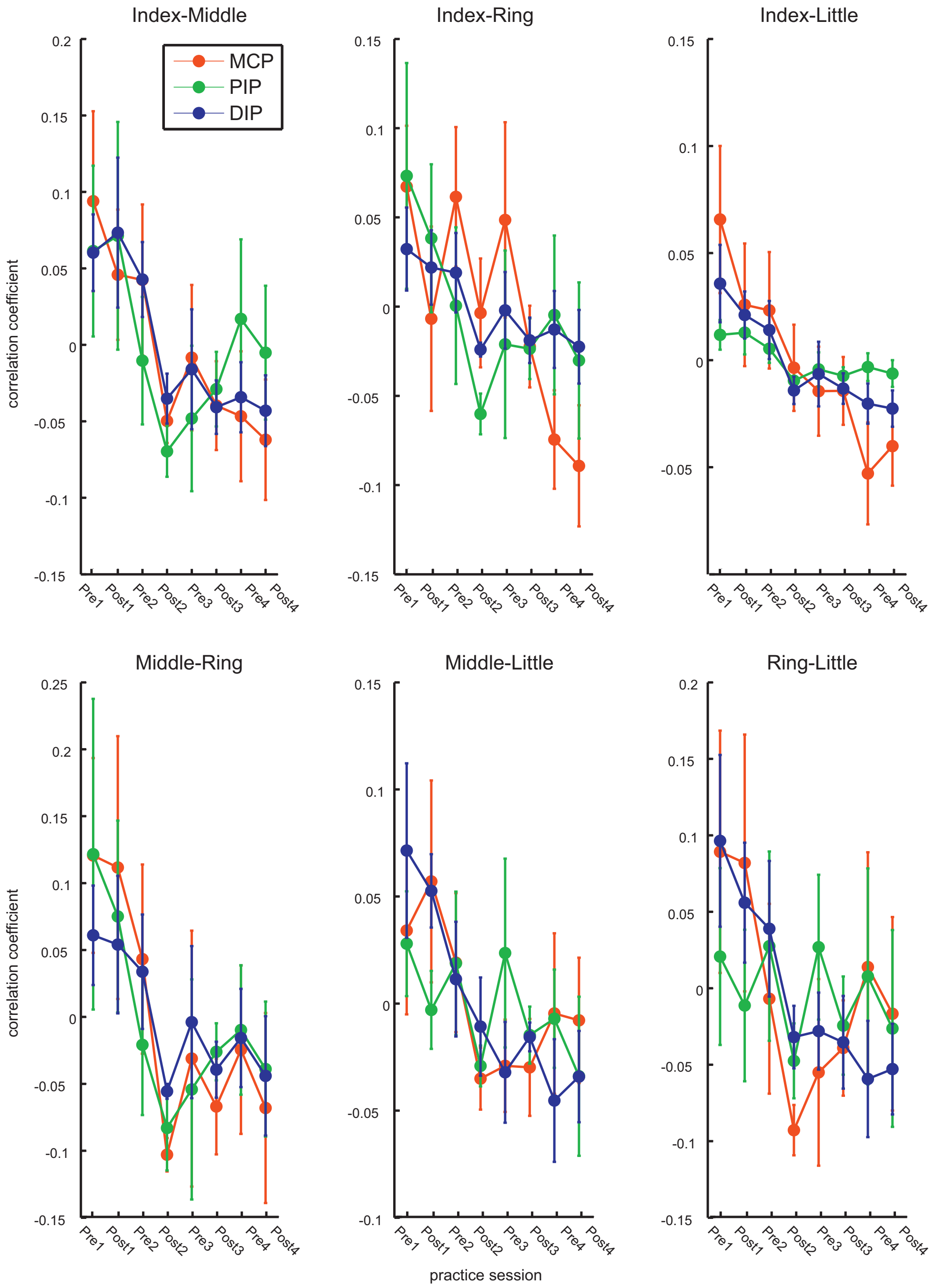

Fig. 3. The group mean of the correlation coefficient values reconstructed by multiplying the correlation coefficients of the pvPC and its corresponding weighting coefficients over four days of practice (=eight practice sessions) for each pair of index, middle, ring and little fingers at the MCP (red), PIP (green), and DIP (blue) joints. An error bar represents one standard error across participants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 1C shows the group mean of variance accounted for by the first 2 PCs. Overall, the piPC accounted for more than 70% of the total variance, and the pvPC accounted for approximately 10% of the total variance.

Fig. 2 shows the time-varying pvPC waveforms that represent the joint angular velocity at the MCP, PIP, and DIP joints of the fingers in one representative participant. Overall, the joint angular velocity of pvPC covaried across fingers. For example, during the first keystroke with the ring finger (i.e., the first “R” in Fig. 2), the ring finger rotated in the same direction as the remaining three fingers, particularly at the MCP joint. The correlation coefficient of the joint angular velocity between the striking and non-striking finger at the pairs of index–middle, index–ring, index–little, middle–ring, middle–little, and ring–little for the pvPC was 0.49, 0.20, 0.23, 0.46, 0.34, and 0.33 at the MCP joint, 0.18, 0.19, 0.06, 0.02, 0.10, and 0.42 at the PIP joint, and 0.29, 0.21, 0.13, 0.29, 0.06, and 0.51 at the DIP joint, respectively. The positive coefficient values confirm covariation of joint motion across fingers for the pvPC.

The observation of the movement pattern that represents the covariation of joint rotation across fingers for the pvPC and the progressive decrease of the corresponding WC value with practice indicate that the pvPC functions to decrease the amount of movement covariation across fingers with practice. To assess a role of the pvPC in changes of finger movement organization in relation to practice, we computed a scalar product of the correlation coefficients of pvPC waveforms and the corresponding

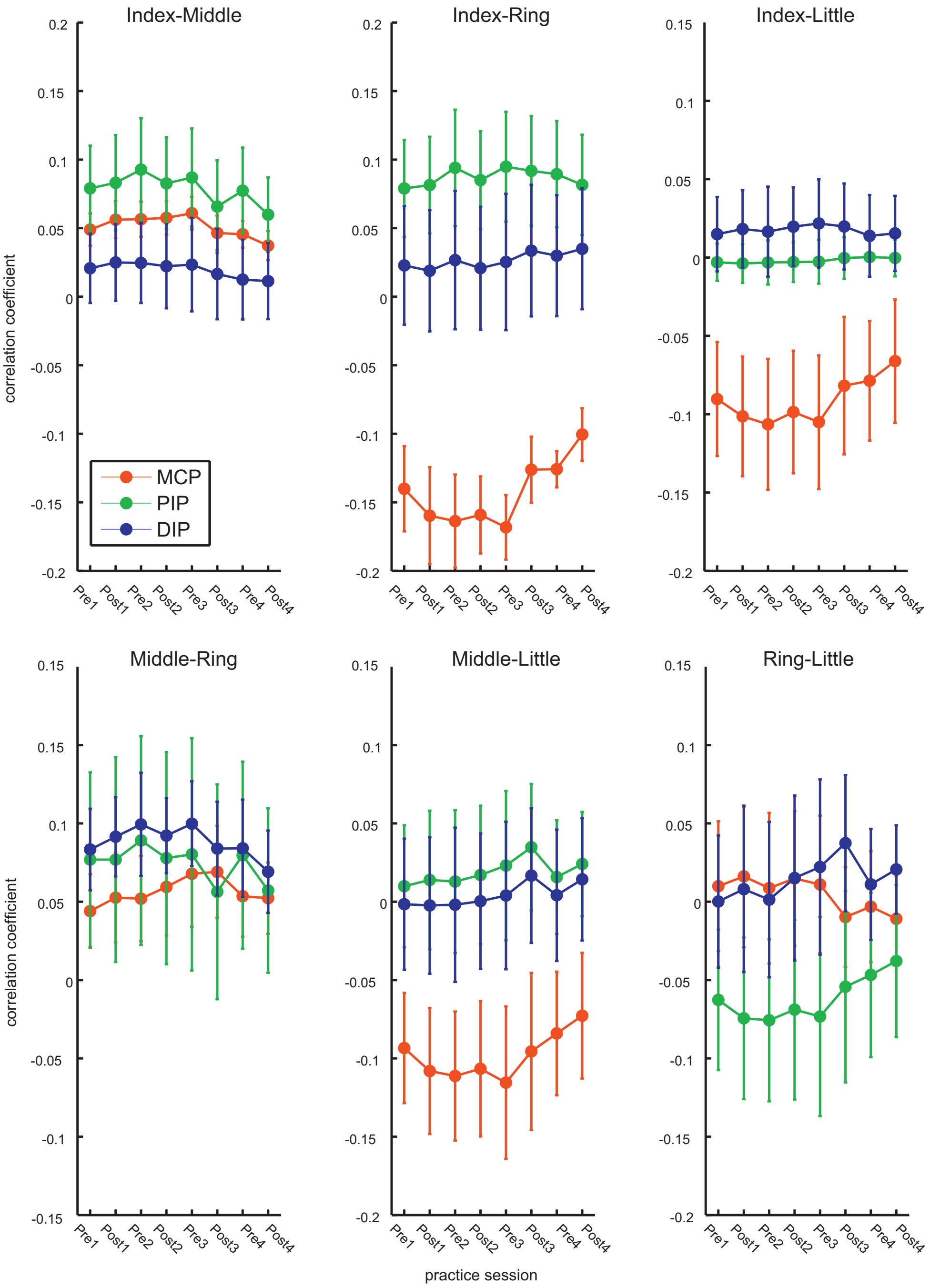

Fig. 4. The group mean of the reconstructed correlation coefficient values using the piPC and its corresponding weighting coefficients over practice sessions for each pair of the four fingers at the MCP (red), PIP (green), and DIP (blue) joints. An error bar represents one standard error across participants. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

weighting coefficient values at each session for each participant. The reconstructed correlation coefficients over the 8 practice sessions represent the amount of contribution of the pvPC to changes in the amount of movement covariation with practice. Fig. 3 depicts the group mean values of the reconstructed correlation coefficient values at all finger pairs over the 8 practice sessions for the pvPC. Overall, all pairs of fingers at each joint demonstrated a decrease of the coefficient value with practice. This confirms that the pvPC played a role in the progressive decrease of the movement covariation across fingers with practice. A linear regression analysis was performed for the group mean values at each pair of fingers. Table 1 summarizes the result, which shows a significant decrease of the reconstructed correlation coefficient with practice at most finger pairs, particularly of the MCP and DIP joints.

Similarly, correlation coefficient values were also reconstructed using piPC, and Fig. 4 depicts the group mean values at all finger pairs over the 8 practice sessions. Overall, the correlation coefficient values were constant across the sessions at all finger pairs and joints. Although a linear regression identified significant changes with practice at some finger pairs and joints (Table 1), their regression coefficients were all fairly small and close to zero (<0.01). The result confirms a lack of apparent changes in the amount of the movement covariation across fingers with practice for PiPC.

Table 1
Results of linear regression analysis for the reconstructed correlation coefficients from piPC and pvPC.

	piPC	Regression coefficient	R^2	p	pvPC	Regression coefficient	R^2	p
MCP	WC1 × r^{IM}	−0.002	0.35	0.121	WC2 × r^{IM}	−0.021	0.81	**0.002**
	WC1 × r^{IR}	0.007	0.45	0.068	WC2 × r^{IR}	−0.019	0.64	**0.017**
	WC1 × r^{IL}	0.004	0.50	0.050	WC2 × r^{IL}	−0.015	0.91	**<0.001**
	WC1 × r^{MR}	0.001	0.17	0.305	WC2 × r^{MR}	−0.027	0.61	**0.023**
	WC1 × r^{ML}	0.004	0.36	0.116	WC2 × r^{ML}	−0.009	0.42	0.082
	WC1 × r^{RL}	−0.004	0.65	**0.016**	WC2 × r^{RL}	−0.014	0.27	0.183
PIP	WC1 × r^{IM}	−0.003	0.42	0.084	WC2 × r^{IM}	−0.009	0.21	0.260
	WC1 × r^{IR}	0.001	0.08	0.491	WC2 × r^{IR}	−0.012	0.46	0.065
	WC1 × r^{IL}	0.001	0.78	**0.004**	WC2 × r^{IL}	−0.003	0.63	**0.019**
	WC1 × r^{MR}	−0.003	0.31	0.151	WC2 × r^{MR}	−0.018	0.43	0.079
	WC1 × r^{ML}	0.002	0.43	0.078	WC2 × r^{ML}	−0.006	0.38	0.103
	WC1 × r^{RL}	0.004	0.59	**0.025**	WC2 × r^{RL}	−0.004	0.11	0.429
DIP	WC1 × r^{IM}	−0.002	0.66	**0.014**	WC2 × r^{IM}	−0.018	0.78	**0.004**
	WC1 × r^{IR}	0.002	0.68	**0.012**	WC2 × r^{IR}	−0.008	0.72	**0.008**
	WC1 × r^{IL}	0.000	0.00	0.881	WC2 × r^{IL}	−0.008	0.87	**0.001**
	WC1 × r^{MR}	−0.002	0.26	0.199	WC2 × r^{MR}	−0.015	0.64	**0.017**
	WC1 × r^{ML}	0.002	0.64	**0.018**	WC2 × r^{ML}	−0.016	0.84	**0.001**
	WC1 × r^{RL}	0.003	0.42	0.081	WC2 × r^{RL}	−0.022	0.87	**0.001**

A bold number indicates $p < 0.05$. WC1: weighting coefficient of piPC, WC2: weighting coefficient of pvPC. r: correlation coefficients between two fingers. I, M, R, and L indicates the index, middle, ring, and little finger, respectively.

4. Discussion

The present study investigated a methodological advantage of PC analysis for assessing the reorganization of hand movements during a course of piano practice. The results demonstrated that the PC analysis successfully extracted two distinct movement patterns; one of these remains during practice, and the other decreases with practice. The latter pattern was characterized by covariation of movements across fingers. The finding that this movement element diminished during a course of practice indicated a decrease of movement covariation and thus a facilitation of the individuated finger movements. To the best of our knowledge, this is the first study that uses PC analysis to identify a specific movement pattern that varies with practice. Therefore, it is possible that this analytical technique serves as an effective means that describes practice-related reorganization of DOFs of the motor system in a variety of complex motor behaviors that involve motions at a large number of joints, such as object manipulation, finger-spelling, and surgery. It is also likely that the current method can identify maladaptive reorganization of movements by a development of movement disorders such as focal hand dystonia [2,12,13].

Our observation of the facilitation of movement independence across fingers through piano practice was in agreement with the findings of previous studies that compared pianists of different skill levels. For example, during repetitive piano keystrokes, skilled pianists showed a smaller amount of spillover of finger force exertion into the adjacent fingers than unskilled piano players [17]. Our recent study also found equal independence of movements across fingers for pianists [4], which is different from non-musicians, who showed lower movement independence at the middle and ring fingers than at the other fingers [10]. The present finding extends these findings by showing a causal relationship between piano practice and independent finger control. Presumably, the facilitation of independent movement control is associated with the improved maximum speed of piano playing after daily practice [6].

By contrast, the movement pattern independent of the practice accounted for more than 70% of the total variance of movements. This highlights robustness of the hand movement pattern against training. The movement pattern was characterized by negative coupling between the index and ring fingers, between the index and little fingers, and between the middle and little fingers. This multi-finger coordination pattern is similar to the pattern observed during dexterous hand grasping [8,19]. Robustness of this coordination pattern against the short-term practice may explain why musicians undergo more than 10,000 h of practice before age 20 [15].

One limitation of the present study was a lack of understanding of the roles of higher PCs. The PC analysis found that the first two PCs accounted for 81.2% of the variance of movements. This indicates that higher PCs accounted for 18.8% of the total variance of movements. Although our PC analysis demonstrated that higher PCs did not display any common trends across the participants, it is possible that these PCs functioned to either increase or decrease the movement independence at specific finger pairs. Previous studies have shown that the higher PCs of the hand movements are not noise but are rather responsible for the dexterous control of fingers [19]. A further study is needed to uncover the roles of higher PCs in the movement reorganization of the hand through piano practice.

Conflict of interest statement

The authors declare that there are no conflicts of interest.

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